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FLIGHT TESTS OF A 0.13-SCALE MODEL OF A VECTORED-THRUST

JET VTOL TRANSPORT AIRPLANE

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SUMMARY

An experimental investigation has been made to determine the dynamic stability and control characteristics of a 0.13-scale flying model of a vectored-thrust jet vertical-take-off-and-landing (VTOL) airplane in hovering and transition flight. In hovering flight in still air the model could be flown smoothly and easily, and there was no noticeable change in trim, stability, or lift due to proximity to the ground for hovering flight when the model wheels were 3 inches or more above the ground. Vertical take-offs and landings in still air could be made smoothly and easily although there was a longitudinal trim change caused by a nose-up pitching moment when the wheels were less than 2 inches above the ground. Transitions from hovering to forward flight and back to hovering could be made smoothly and consistently. The model was longitudinally stable in the high-speed part of the transition range and in low-speed conventional flight, but was neutrally stable in the low-speed part of the transition range. However, the motions associated with this neutral stability were very mild because of the low speeds involved and could be controlled easily. In both the transition and low-speed conventional-flight conditions, the lateral motions required constant attention in order to prevent a divergence in roll, as if the model had very low effective dihedral, but these motions could be controlled fairly easily because the rate of divergence was low. In the low-speed conventional-flight condition, the yawing motions were more difficult to control than in the transition because of a tendency of the model to wander in yaw (a few degrees to either side) in a random manner. These motions were not divergent and did not result in an unflyable condition but were annoying to the pilot. In the landing approach condition with engine exhaust nozzles deflected 80° to 100°, the longitudinal stability was about the same as in the transition from hovering to forward flight; the lateral motions were stable and well damped; and the directional stability was good. Short take-offs and landings could be made smoothly and consistently at various nozzle deflections with no noticeable change in trim or control effectiveness.

INTRODUCTION

An investigation has been made to determine the low-speed dynamic stability and control characteristics of a 0.13-scale flying model of a vectored-thrust jet vertical-take-off-and-landing (VTOL) transport airplane in hovering and transition flight. This airplane has a straight wing mounted on top of the fuselage and is powered by two vectored-thrust turbofan engines mounted in nacelles under the wing and six turbojet lift engines mounted in wing-tip pods with three engines in each pod. Take-offs and landings with the airplane in a horizontal attitude are made with the nozzles of the vectored-thrust engines rotated so that the exhaust is directed downward and the lift engines, which are in a vertical attitude, turned on. In forward flight the nozzles of the vectored-thrust engines are rotated so that the exhaust of the engines is directed to the rear and the lift engines are turned off. Control of hovering and low-speed flight is provided by jet-reaction controls located at the rear of the fuselage and on the wing tips. Conventional aerodynamic controls consisting of ailerons, rudder, and an elevator are provided for control in normal forward flight.

The investigation consisted of:

(1) Free-flight tests in still air for study of the hovering and vertical take-off and landing conditions

(2) Free-flight tests in the Langley full-scale tunnel for study of slow constant-altitude transitions

(3) Control-line tests for study of longitudinal stability and control in rapid transitions and short take-offs and landings

(4) Force tests to supplement the flight tests

SYMBOLS

The longitudinal forces and moments are referred to the wind-axis system and the directional and lateral forces and moments are referred to the body-axis system which originates at the center of gravity of the model.

b wing span, ft

C_D drag coefficient, $\frac{D}{qS}$

C_L lift coefficient, $\frac{L}{qS}$

C_l rolling-moment coefficient, $\frac{M_X}{qSb}$

C_m pitching-moment coefficient, $\frac{M_Y}{qS\bar{c}}$

C_n yawing-moment coefficient, $\frac{M_Z}{qSb}$

C_Y lateral-force coefficient, $\frac{F_Y}{qS}$

$\bar{c}$ mean aerodynamic chord, M.A.C., ft

cg center of gravity

D drag, lb

F_Y lateral force, lb

I_X, I_Y, I_Z moment of inertia about X-, Y-, and Z-axis, respectively, slug-ft^2

L lift, lb

L_o lift for the condition of zero longitudinal acceleration, lb

M_X rolling moment, ft-lb

M_Y pitching moment, ft-lb

M_Z yawing moment, ft-lb

q dynamic pressure, lb/sq ft

S wing area, sq ft

T_j static thrust of lifting engines, lb

α angle of attack of fuselage reference line with the horizontal, deg

β angle of sideslip, deg

Δ angle of nozzles of vectored-thrust engines relative to fuselage reference line, deg

δ_f wing-flap deflection, deg

MODEL

A photograph of the 0.13-scale model is presented in figure 1 and sketches showing some of the more important model dimensions are presented in figures 2 to 4. The geometric characteristics of the model are presented in table I, and the mass characteristics are presented in table II. The engine exhaust nozzles on the sides of the engine nacelles rotated through angles as great as 100° ($\Delta = 0^\circ$ to 100°) for various phases of the transition and vertical take-off and landing maneuvers. The large vertical tail shown in figure 2 was provided for some special tests to study directional stability in conventional flight and was not used for any other tests.

The vectored-thrust engines of the airplane were simulated on the model by ducted fans driven by compressed-air jets at the tips of the fan blades (fig. 3). These power plants gave a reasonably accurate simulation of the engine of the full-scale airplane from an aerodynamics point of view as explained in the remainder of this paragraph. It was not possible, of course, to represent exactly the characteristics of the full-scale turbofan engine with the cold airflow of the model. In order to represent the jet interference properly, it was believed necessary to duplicate the thrusts of the individual nozzles correctly and to represent approximately the proper size of the jet stream from each nozzle. In order to represent the aerodynamic effects of the inlet, it was believed necessary to have the proper scaled-down inlet mass flow. For the exhaust simulation, therefore, the individual thrusts of the front and rear nozzles were correctly scaled and the total exhaust nozzle area was exactly the true scaled value. With these two characteristics set, the front nozzles were slightly larger than scale size; the rear nozzles were slightly smaller than scale size; and therefore, the exhaust streams were only approximately the correct scale size. With the exhaust flow represented in this manner, the inlet mass flow was about 90 percent of the correct scaled-down mass flow. The necessary difference in gas-flow momentum between the inlets and exits on the model was made up by the addition of the compressed air required to drive the fan instead of by heat as is the case for the full-scale engine. The adequacy of the simulation was not checked for forward-flight conditions but the simulation must have been reasonably good since the conditions for flight (i.e., lift equals weight and drag-lift ratio determined by the flight path to be simulated) required that the exhaust momentum, or thrust, be correctly represented.

The lift engines were simulated by compressed-air jets exhausting into ejector tubes - three ejectors to a pod at each wing tip as shown in figure 4. When installed in this manner, the compressed-air jet acted as a jet pump to produce a flow of air through the pod. With this arrangement the correct thrust and approximately the proper size of the jet stream of each engine were represented.

Control for hovering flight was obtained by means of jet-reaction controls located at the rear of the fuselage and on the wing tips. Roll control was obtained by reducing the thrust of the jets in one wing-tip pod and increasing the thrust of the jets in the other wing-tip pod. Pitch and yaw control was obtained by redirecting the thrust of a pair of compressed-air jets located at the rear of the fuselage. The air for the pitch and yaw jets was obtained by bleeding the air supply to the ducted fans. The moment produced by all the jet-reaction controls therefore varied with the power required to fly. The calibration of the pitch and roll jet controls is presented in figure 5. The yaw control produced a control force of 11 percent of the pitch jet force.

The aerodynamic controls for forward flight consisted of conventional ailerons, rudder, and elevator. Each of these controls could be operated separately or in conjunction with the jet-reaction controls.

All controls (aerodynamic and jet) were of the flicker type (full on or off) with integrating trimmers. These trimmers trimmed the control a small amount in the direction the control was moved each time a control deflection was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition. The aerodynamic-control deflections applied by a flick of the controls were as follows:

Elevator deflection, deg	±20
Rudder deflection, deg	±20
Aileron deflection, deg	±20

TESTS AND TEST TECHNIQUE

Flight Tests

Basic test setup.- The basic setup used in testing free-flight models is illustrated in figure 6. This sketch shows the pitch pilot, the safety-cable operator, and the power operator on a balcony at the side of the open test section of the Langley full-scale tunnel. The roll and yaw pilots were located in an enclosure in the lower rear part of the test section. The pitch, roll, and yaw pilots were thus located at the best available vantage points for observing and controlling the particular phase of the model motion with which each was concerned. Motion-picture records were obtained with fixed cameras mounted near the pitch pilot and at the top rear of the test section.

The air for the ducted-fan power units, wing-tip jets, jet controls, and control actuators was supplied through flexible plastic hoses while power for the electric trim motors and control solenoids was supplied through wires. These wires and tubes were suspended overhead and taped to a safety cable (1/16-inch braided aircraft cable) from a point approximately 15 feet above the model down to the model. The safety cable, which was attached to the top of the wing over the center of gravity, was used to prevent crashes in the event of a power or control failure or in the event that the pilots lost control of the model. During the flight the cable was kept slack so that it would not appreciably influence the motions of the model. The thrusts of the ducted-fan power units and the jets in the wing-tip pods were adjusted by means of valves in the air-supply lines, with approximately 35 feet of flexible hose between the valves and the model. This long length of hose between the throttling valves and the model motors, together with the time required to change the speed of the fans, caused considerable lag in the thrust control which was somewhat objectionable, but was no worse than the lag in other systems used to power free-flight models.

Hovering flight tests.- The hovering flight tests were made in still air by using an adaptation of the test setup just described. In these tests the model was hovered at heights of 5 to 15 feet above the ground to determine the dynamic stability and control characteristics out of ground effect. Hovering flights were also made at very low heights (wheels 3 to 12 inches above the ground) to study the effects of the ground proximity on the lift, trim, and stability of the model. Along with the hovering flight tests, vertical take-offs and landings were also made to study the behavior of the model in these transient conditions.

Slow transitions.- Transition flight tests were made in the test section of the full-scale tunnel by using the previously described test setup to determine the overall stability and control characteristics of the model in transition flight from hovering to forward flight. The technique of making a transition flight in the test section of the full-scale tunnel is best explained by describing a typical flight.

The model hung from the safety cable and the power was increased until the model was in steady hovering flight. At this point the tunnel drive motors were turned on and the airspeed began to increase. As the airspeed increased, the flight controls and power were operated and the nozzles on the sides of the nacelles were rotated so that the jets were tilted progressively to maintain the position of the model in the test section as the transition to normal forward flight was performed. Transitions made in this manner were limited to very low rates of acceleration because of the slow rate at which the tunnel airspeed could be increased. Of course, it was also possible to hold the tunnel speed constant at various values in the transition range so that the model could be flown for extended periods of time at various stages in the transition range for detailed study of its behavior in these conditions. It was also possible to make transitions from forward flight back to hovering by reducing the airspeed in the tunnel, but there was little difference between the conditions for slow-down and speed-up transitions in the tunnel because of the low rates of change of tunnel speed that could be obtained. In most cases the flight was terminated by gradually taking up the slack in the safety cable while reducing the power to the model.

The transitions were slow constant-altitude transitions and covered a speed range from about 0 to $48\frac{1}{2}$ knots (full-scale airspeeds from 0 to 135 knots), angles of attack from 3° to 15°, and flap deflections of 0° and 60°. A limit of $48\frac{1}{2}$ knots on the tunnel airspeed was selected because it is the point where a pole change on the tunnel drive motors is required for higher speeds. This pole change causes a decided lag in the buildup of airspeed which is inconvenient and was avoided in the present tests. Because of the acceleration limitations of the tunnel drive system, the minimum time in which a transition to $48\frac{1}{2}$ knots could be made was approximately 85 seconds.

Descent flight.- One of the techniques proposed for the landing approach of the airplane is to start the approach by reducing power to idle and rotating the nozzles of the vectored-thrust engines to a deflection of 80° or 100°. Then the lifting engines in the wing-tip pods are brought up to the proper thrust level for the particular aircraft weight. As the airspeed drops off and the wing and lifting engines are no longer capable of supporting the airplane, the thrust of the vectored-thrust engines is gradually increased to maintain the necessary lift until the airplane comes to a stop in hovering flight.

Flight tests were made in the full-scale tunnel to determine the dynamic stability and control characteristics of the model in this landing-approach condition. In order to simulate the condition in the tunnel, the model was propelled with a compressed-air jet exhausting rearward from the rear of the fuselage so that the model could be flown in steady level flight with the nozzles of the vectored-thrust engines at an arbitrary deflection and thrust setting that would not propel the model in level flight. The thrust of this jet effectively represented the forward component of the weight of the airplane along the flight path in a gliding descent or the inertia force due to longitudinal deceleration. This device therefore made it possible to duplicate the aerodynamic forces, engine thrust, and nozzle-deflection conditions corresponding to descent or deceleration conditions with the model flying in level constant-speed flight in the tunnel. These tests were performed at angles of attack of 10° and 15°, simulated glide-path angles of 10° and 15°, forward speeds of 65 to 92 knots (full scale), and nozzle angles from 80° to 100°.

Low-speed conventional flight.- The dynamic stability and control of the model in low-speed conventional flight and at the high-speed end of the transition where the nozzles of the vectored-thrust engines were at 0° deflection was investigated by using the same basic testing technique used in the transition tests. These tests covered a speed range from 135 to 167 knots (full scale) and an angle-of-attack range from 3° to 12° for both the flap-up and flap-down conditions.

Rapid transitions.- The dynamic stability and control characteristics of the model in rapid transition from hovering to forward flight and back to hovering were investigated by using an adaptation of the basic free-flight model testing technique. The control-line equipment, which employs an adaptation of the previously described free-flight model test setup, is illustrated in figure 7 and described in detail in reference 1. Basically the control-line equipment consists of a crane with a jib boom to provide an overhead support for the safety cable. The pilot and operators ride in the cab of the crane so that they will always face the model as it flies in a circle at the end of a restraining line which opposes the centrifugal force. The restraining line enters the model at the center of gravity and provides some restraint of the lateral freedom of the model but does not affect the longitudinal freedom. The crane is mounted on a pedestal in the middle of a large concrete apron located in a wooded area which serves as a windbreak. With this equipment rapid transition flights from hovering to normal forward flight, or vice versa, can be made since the crane has a high rate of acceleration. Actually, the crane can accelerate rapidly enough to keep up with a forward or rearward model acceleration of 1g.

The technique of performing a rapid-transition flight on the control-line equipment is also best explained by describing a typical transition flight. The model hung from the safety cable and the power was increased until the model was in steady hovering flight. At this point the nozzles of the vectored-thrust engines were rotated to propel the model forward; the crane was rotated to keep up with the model; and the pitch control and power of the model were operated to maintain a constant angle of attack and constant altitude during transition to forward flight (nozzles straight back (0° deflection), and lift engines turned off).

Slow-down transitions were performed by starting with the model in normal unaccelerated forward flight at an angle of attack of about 10° with the nozzles at 0° deflection. The nozzles were then rotated to 100° deflection at a rate of 22° per second without changing the throttle setting from the relatively low power required for low-speed forward flight. It was, of course, necessary to reduce the angle of attack somewhat as the nozzles rotated to prevent the model from climbing. Then, as the model slowed down, the angle of attack was brought back to about 10° and the thrust of the lifting engines in the wing-tip pods was increased up to their hovering thrust level to keep the lift constant as the speed dropped off. In order to increase the deceleration of the model further, the angle of attack was increased and the throttle to the main engines was advanced to maintain the necessary lift. After the forward motion of the model had been stopped, the angle of attack was again reduced to about 10° and the thrust of the main engines was adjusted to maintain hovering flight. The longitudinal stability, control, and trim characteristics of the model were studied during such rapid transitions, especially to note any differences from those noted in the more detailed studies during the slow-transition tests in the tunnel.

Short take-offs and landings.- For the purpose of this discussion, a "short" take-off or landing will be defined as any take-off from the ground in which the wing lift is supplemented by thrust from the tip pod engines or by a component of thrust resulting from the deflection of the main-engine nozzles from the cruise position. The tests were performed by using the control-line technique previously described with the model actually making rolling take-offs and landings from the concrete apron of the flying circle around the crane. These tests are not considered to have produced accurate simulation of full-scale performance characteristics such as acceleration or length of ground roll. The poor simulation of these characteristics resulted from several factors: First, the engine nozzles could not be rotated at scale speed, so all take-offs and landings were made at fixed nozzle settings; second, it is not known how the variation of thrust with forward speed of the model compares with the full-scale machine; third, the landing gear of the model did not give a scale value for rolling friction and had no brakes. These three factors, however, were of little or no importance with regard to the main point of the tests, which was the investigation of the longitudinal static and dynamic stability during take-off, climbout, and landing.

Take-offs were performed with fixed nozzle angles of 0°, 30°, 45°, and 60° with and without the tip jets operating. In the cases where the tip jets were operating, the static thrust-to-weight ratio was held at 0.9. That is, the sum of static thrust of the tip jets plus the static thrust of the vectored-thrust engines was equal to 0.9 of the weight of the model. In this case the tip jets were operating at 32 pounds of thrust which is their rated hovering thrust, and the vectored-thrust engines were producing 43 pounds of thrust which is about 84 percent of their hovering thrust of 51 pounds. In the take-off without the tip jets operating, the vectored-thrust engines produced 54 pounds of static thrust which is about 1.04 percent of their hovering thrust giving a thrust-to-weight ratio of 0.64.

Landings were also made for fixed nozzle angles of 60° and 100° with the tip jets operating and a maximum available thrust-to-weight ratio of 0.9. In the 60° nozzle-angle case the model was first flown in unaccelerated forward flight with the nozzles at 60°. Then the power was reduced, and the angle of attack was adjusted to make a descent and then a landing. In the 100° nozzle-angle case the model was first flown in unaccelerated forward flight at an arbitrary nozzle angle; then the nozzles were quickly rotated to 100° and the angle of attack and power were adjusted to establish the descent and flare.

Force Tests

A few force tests of the model were made in the test section of the Langley full-scale tunnel in an effort to determine the static longitudinal and directional stability of the model. The longitudinal force tests were made at various nozzle angles for a range of power settings to cover both the transition and conventional flight conditions. The lateral force tests were made only to determine the static directional and lateral stability of the model in the low-speed conventional flight condition. With the exception of the power-off tests, the force tests were made with the power settings required to balance the drag along the wind axis for several angles of attack at the zero sideslip condition. These tests, therefore, duplicated the condition of flight at zero longitudinal acceleration which was the condition for the free-flight tests in the Langley full-scale tunnel. Most of the tests were made with the model in the original, or basic, condition with the flaps deflected, but a few tests were made with the vertical tail area increased and with the flaps retracted to study the effect of each of these changes on the static directional and lateral stability.

RESULTS AND DISCUSSION

A motion-picture film supplement illustrating the flight-test results has been prepared and is available on loan. A request card form and a description of the film will be found on the page with the abstract cards.

Hovering Flight

When hovering in relatively still air, the model could be flown smoothly and easily. The yawing motions, of course, were about neutrally stable; and there was a mild divergence in pitch and roll which seemed to be a simple divergence and not an unstable oscillation. This divergence was fairly easy to control because of the low rates of motion involved. In hovering flight near the ground (wheels about 3 to 12 inches (model scale) above the ground) there was no apparent change in trim, stability, or lift due to the proximity of the ground.

A comparison of the jet-reaction controls used in the model tests with those of the airplane in terms of angular acceleration produced by the control about its respective axis is presented as follows:

	Angular acceleration, radians/sec^2	
Axis	Airplane	Model (scaled up)
Pitch	0.40	0.46
Roll	.54	.33
Yaw	Not available	.05

These pitch- and roll-control powers were found to be satisfactory for the very limited task evaluated - maintaining smooth steady flight in still air. The yaw-control power was barely acceptable even for this limited task, but the adequacy of the controls for more severe tasks was not evaluated because the model was accidentally destroyed before that part of the program was undertaken.

Vertical Take-Off and Landing

Vertical take-offs and landings in still air could be made smoothly and easily. There was no evidence of any ground effect on either the lift or stability of the model. There was, however, a nose-up change in longitudinal trim when the wheels were less than about 2 inches above the ground. Although the model experienced this pitch-trim change in all the take-off and landing tests, the pilot had no difficulty in controlling the model with the pitch control available, which, as shown in the preceding section, was slightly more powerful than the true scaled pitch control of the airplane.

Slow-Transition Flight

Longitudinal characteristics.- Slow constant-altitude transition from hovering to $48\frac{1}{2}$ knots (135 knots (full scale)) could be made smoothly and consistently, with only moderate changes in longitudinal trim, in the test section of the full-scale tunnel or on the control-line equipment. These slow-transition tests were made with flaps up and with flaps down, and there was no noticeable difference in the longitudinal stability and control characteristics of the model due to deflecting the flaps. At any given speed in the transition, the model could be flown over a wide angle-of-attack range. The maximum angle of attack through the speed range was determined by either wing stall at the lower speeds or lift required for level flight at the higher speeds. The lower limit of the angle-of-attack range was determined by the amount of thrust used on the wing-tip lifting engines. The lifting engines caused only a slight change in the longitudinal trim and had no apparent effect on the stability. Flights made at angles of attack near the stall were difficult to control because of the intermittent stalling and unstalling of the wing. However, at angles of attack where the wing was completely stalled, the model was somewhat easier to control.

In the flight tests, the model was found to have about neutral static longitudinal stability at the low-speed end of the transition range (high nozzle angles) and to become stable at the high-speed end (low nozzle angles). This result is supported by the force-test results in figures 8 to 11. The neutral stability at low speeds is probably mainly the result of low free-stream dynamic pressures involved which would make all the aerodynamic forces and moments low.

A considerable amount of nose-down trim was required in the low-speed part of the transition range, but at the high-speed end of the range little or no control moment was required for trim. The nose-down trim required at low speeds caused some difficulty in the tests in that the nose-down control remaining for maneuvering after the model was trimmed was small, and, at times, the pilot was unable to check the upward motion resulting from a nose-up pitching disturbance within the confines of the tunnel. This problem would be expected to be less troublesome in an airplane in free air where greater changes in speed and height can be tolerated. The percentage of the available control that was required for trim at low transition speeds was not determined, but an estimate of the general magnitude can be made from the force-test results of figure 11(b) which were obtained for a representative condition. These data, for $T_j/L_o = 0.39$ which is very close to the value 0.40 generally used in the flight tests, show that a nose-down moment $M_Y/L_o\bar{c}$ of 0.07 was required for trim. This moment corresponds to about 1/3 of the jet-reaction control available with the vectored-thrust engines producing hovering thrust. Since these engines were throttled back considerably in the transition, it seems likely that the pitching moment available after trim in the low-speed part of the transition range was less than 1/2 that available for maneuvering in hovering. This would be a significant reduction in control power.

Lateral characteristics.- The lateral characteristics of the model in transition were, in general, satisfactory. There seemed to be very little dihedral effect, so that constant attention to the roll control was required to prevent a divergence, but because the rolling motions were relatively mild, the model was considered easy to control in roll. As the airspeed increased, the model developed a slight degree of directional stability through the middle part of the transition range, during which very little yaw control was necessary. At high speeds in the transition range, the directional behavior of the model became poor as it began to experience the troublesome random wandering motions in yaw which characterized the behavior of the model in low-speed conventional forward flight. This behavior and attempts to eliminate it are described in detail in a later section entitled "Low-Speed Conventional Flight," since it is in this condition that the directional behavior of the model became the most objectionable and it was in this condition that special tests were made to seek the source of the trouble. No lateral oscillations were observed even after deliberate efforts were made to excite them.

Descent Flight

In the simulated landing approach and transition tests made in the full-scale tunnel by the method previously described for simulating descent and deceleration conditions, angles of attack of 10° and 15°, glide path angles of 10° and 15°, and forward speeds of 65 to 92 knots (full scale) were covered for nozzle angles of 80° to 100° on the vectored-thrust engines. In these tests it was found that the model had about the same longitudinal stability that it did in the level-flight condition at the same speed. However, the pitch control, which is fed by air bled from the vectored-thrust engines, was weaker than desired at the lower airspeeds because of the low power settings on the vectored-thrust engines. The lateral motions of the model were stable and well damped and the directional stability was good. In this connection, it should be noted that all the descent tests were made at speeds below that at which the troublesome random yawing motions had been encountered in the transition tests. At angles of attack near the stall, the model had a wallowing motion due to intermittent stalling and unstalling of the wing, but it was still fairly easy to control because the motions associated with the stall were mild.

Low-Speed Conventional Flight

Longitudinal characteristics.- In low-speed conventional flight and at the high-speed end of the transition where the nozzles of the vectored-thrust engines were at 0° deflection in either the wind-tunnel or the control-line tests, the model was longitudinally stable over the angle-of-attack range (3° to 12°) and speed range 135 to 167 knots (full scale).

Flights were also made both with flaps up and flaps down, and there was no apparent effect on the longitudinal stability and control characteristics of the model due to the flaps.

Lateral characteristics.- In low-speed conventional flight and at the high-speed end of the transition, the model became somewhat more difficult to fly than at the intermediate transition speeds. The roll characteristics of the model were about the same as in the transition but the yawing motions became more difficult to control. This increased difficulty was caused by a tendency of the model to wander in yaw, a few degrees to either side, in a random manner. The yawing motion was not divergent, as the model would trim at some small angle of sideslip to either side of zero. This yawing tendency did not result in an unflyable condition, but was annoying to the pilot and it did make it very difficult to produce flights in which no yaw angle at all developed.

After these yawing characteristics had been noted in the flight tests, some force tests were made to determine the static directional and lateral stability of the model in the low-speed conventional flight condition. The results of these tests are presented in figures 12 to 15. The data in figure 12 show that the model had very low or negative static directional stability at small angles of sideslip and that the directional stability was somewhat worse at the higher angle of attack where most of the flights with 0° nozzle deflection were made. It seemed, therefore, that the cause of the poor directional behavior noted in the flight tests had simply been the result of poor static directional stability. Consequently, additional force tests were made with the nose landing gear removed to find out whether this change would improve the stability. The data in figure 14 show, however, that the nose gear had practically no effect. Force tests were also made with the 50-percent larger vertical tail shown in figure 2. Figures 12 and 13 show that the larger tail made the model stable in both the power-off and power-on conditions. Several flights were made with this larger tail at low angles of attack (3°) where the model should certainly have been directionally stable, but the same random wandering in yaw was encountered as had been observed in the flight tests with the original tail. It seemed, therefore, that the directional-stability problem of the model was more than one of simple static directional instability, so the problem was studied in more detail and the factors investigated in the study are discussed in the following paragraphs.

Since the poor directional behavior had not been experienced with the vectored-thrust engine nozzles deflected it seemed that one possible source of directional trouble might have been a dynamic effect of the exhaust of the vectored-thrust engines which must have been very close to the side of the fuselage and the vertical tail in the 0° nozzle deflection condition. Careful study of the flow with tufts on the fuselage, tail, and rear of the nacelles showed no random séparation and attachment of the jet exhaust such as might have caused random yaw disturbances. In this connection it is interesting to note that comparison of the data of figure 12 with those of figure 13 shows little or no effect of power of the vectored-thrust engines on static directional stability. Flight tests were also made with a compressed-air jet at the rear of the fuselage replacing the thrust of the vectored-thrust engines, and the model was found to behave as badly in yaw as with the vectored-thrust engines operating. This test seemed to rule out the possibility of power effects from the vectored-thrust engines causing the trouble and ended investigations of this possible source of trouble.

It seemed that another possible source of the directional trouble might be a combination of (1) wing stalling if the model were flown entirely on wing lift at high angles of attack with no tip-jet power on, or (2) some dynamic power effect associated with tip-jet operation when flying at low angles of attack at the same speed with the tip jets supporting part of the weight. Random wing stalling at high angles of attack was observed in flight with tufts, but peculiarly, did not seem to cause trouble in roll. Flight tests were also made at low angles of attack with a compressed-air jet exhausting downward from the bottom of the fuselage replacing the thrust of the wing-tip jet engines. These tests showed that the operation of the tip-jet engines had no apparent effect on the directional behavior of the model.

Another possible source of the directional trouble was random stalling of the flaps, but flight tests with the flaps up showed no improvement in the yawing motions.

The test program was ended by a crash during flight tests to determine whether the flight cable could have been responsible for the directional troubles. These tests were terminated before they produced any significant results, but two observations on the subject seem worthwhile. First, the presence of the flight cable did not produce a statically unstable condition. The force tests were made with the flight cable on, and the model was found to have an adequate amount of directional stability in conditions under which, in flight, directional problems were encountered. Second, it seems unlikely that any dynamic effect of the flight-cable motion was responsible for the poor directional behavior of the model since the cable was attached at the center of gravity where it could not impart much yawing moment, and since much smaller models have been flown with a flight cable as large as the one used on the present model without their having had any such poor directional behavior.

The net result of this study of the directional characteristics of the model in the high-speed part of the transition range and the low-speed part of the conventional flight range was inconclusive, as pointed out previously, in that no explanation of the random yawing motions of the model was found, but a number of possible sources of the trouble seemed to have been ruled out.

Rapid Transition Flight

Rapid transitions from hovering to forward flight were made in the control-line tests in as few as 10 seconds (28 seconds (full scale)). This time was as rapid as the transition could be made without loss of a significant amount of altitude. In general, the pilot much preferred to perform the transition quickly instead of slowly since he was not required to control the model for as long a period of time in the low-speed portion of the transition range where it was generally not longitudinally stable.

Slow-down transitions, transition from forward to hovering flight, were made in about 14 seconds (40 seconds (full scale)). It was found that such transitions could be performed very easily and consistently and that the control power was adequate. The total pitch-jet control moment for the model for the power condition at the start of the slow-down transition was 19 foot-pounds (66,400 ft-lb (full scale)). The moment, of course, increased as the thrust was increased during the transition until at hovering it was 25 foot-pounds (113,500 ft-lb (full scale)) for a model weight of 83 pounds (37,700 lb (full scale)).

Short Take-Offs and Landings

In general, short take-offs were easy to perform, with no noticeable change in trim or control effectiveness as the model took off from the ground.

A landing was made with the nozzles at 60°, tip jets operating, with a maximum thrust-to-weight ratio available of 0.9. There was no noticeable ground effect on the trim or control effectiveness. Several landings were also made with the nozzles at 100° deflection, tip jets on, and a maximum thrust-to-weight ratio of 0.9. As with the nozzles at 60°, there was no noticeable change in trim or stability caused by ground effect.

SUMMARY OF RESULTS

The results of a free-flight investigation of the stability and control characteristics of a 0.13-scale model of a vectored-thrust jet VTOL airplane can be summarized as follows:

1. In hovering flight in still air the model could be flown smoothly and easily.

2. In hovering flight near the ground (wheels about 3 to 12 inches model scale above the ground) there was no apparent change in trim, stability, or lift due to the proximity of the ground.

3. Vertical take-offs and landings in still air could be made smoothly and easily although there was a longitudinal trim change caused by a nose-up pitching moment when the wheels were less than about 2 inches above the ground.

4. Transitions from hovering to normal forward flight and back to hovering could be made smoothly and consistently, although the model was found to have neutral static longitudinal stability in the low-speed part of the transition range. The lateral motions required constant attention in order to prevent a divergence in roll, as if the model had very low dihedral effect; however, the model was considered easy to control because the motions were relatively mild.

5. In the landing approach with the engine exhaust nozzles deflected 80° to 100°, the longitudinal stability was about the same as in the transition from hovering to forward flight. The lateral motions were stable and well damped and the directional stability was good.

6. In low-speed conventional flight, the model was longitudinally stable in both the flaps-up and flaps-down condition. The roll characteristics of the model were about the same as in the transition, but the yawing motions became more difficult to control because of a tendency of the model to wander in yaw, a few degrees to either side, in a random manner. These motions were not divergent and did not result in an unflyable condition, but were annoying to the pilot.

7. Short take-offs and landings could be made smoothly and consistently with no noticeable change in trim or control effectiveness.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 31, 1964.

REFERENCE

1. Schade, Robert O.: Flight-Test Investigation on the Langley Control-Line Facility of a Model of a Propeller-Driven Tail-Sitter-Type Vertical-Take-Off Airplane With Delta Wing During Rapid Transitions. NACA TN 4070, 1957.

TABLE I

GEOMETRIC CHARACTERISTICS OF MODEL

Wing:	
Sweepback of leading edge, deg	3
Airfoil section	Unknown, templates furnished by manufacturer
Aspect ratio	5.48
Area, sq ft	8.69
Span, ft	6.90
Mean aerodynamic chord, ft	1.28
Incidence angle, deg	3
Dihedral angle, deg	0
Overall length of model, ft	7.58
Vertical tail:	
Sweepback of leading edge, deg	36
Airfoil section	NASA 63_2A015 mod.
Aspect ratio	0.68
Area, sq ft	4.75
Height, ft	1.8
Horizontal tail:	
Sweepback of leading edge, deg	13
Airfoil section	NASA 63_2A015 mod.
Aspect ratio	3.34
Area, sq ft	2.66
Span, ft	2.98
Jet controls:	
Distance of roll jets from fuselage center line, ft	3.61
Distance of pitch jet from center of gravity, ft	4.58
Distance of yaw jet from center of gravity, ft	4.55
Engine exhaust nozzles:	
Total area of forward nozzles, sq in.	18.84
Total area of rear nozzles, sq in.	17.64

TABLE II

MASS CHARACTERISTICS OF MODEL

Weight:	
With landing gear, lb	83
Without landing gear, lb	80.3
Control-line tests, with landing gear, lb	83
Distance of center of gravity from leading edge of M.A.C., percent M.A.C.	22
Moments of inertia (without landing gear):	
I_X, slug-ft^2	7.46
I_Y, slug-ft^2	7.15
I_Z, slug-ft^2	13.45

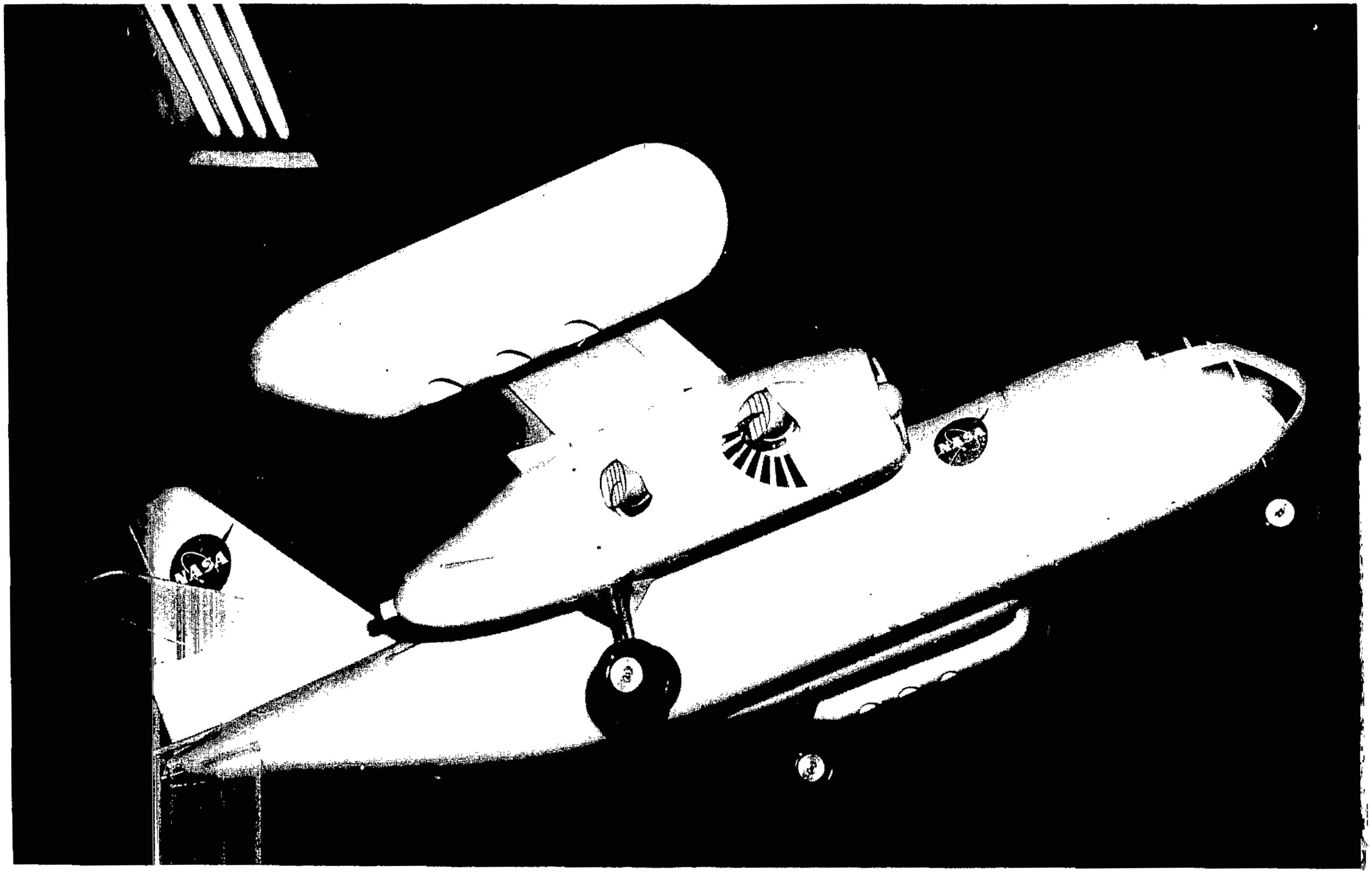


Figure 1.- Photograph of model. L-62-7315

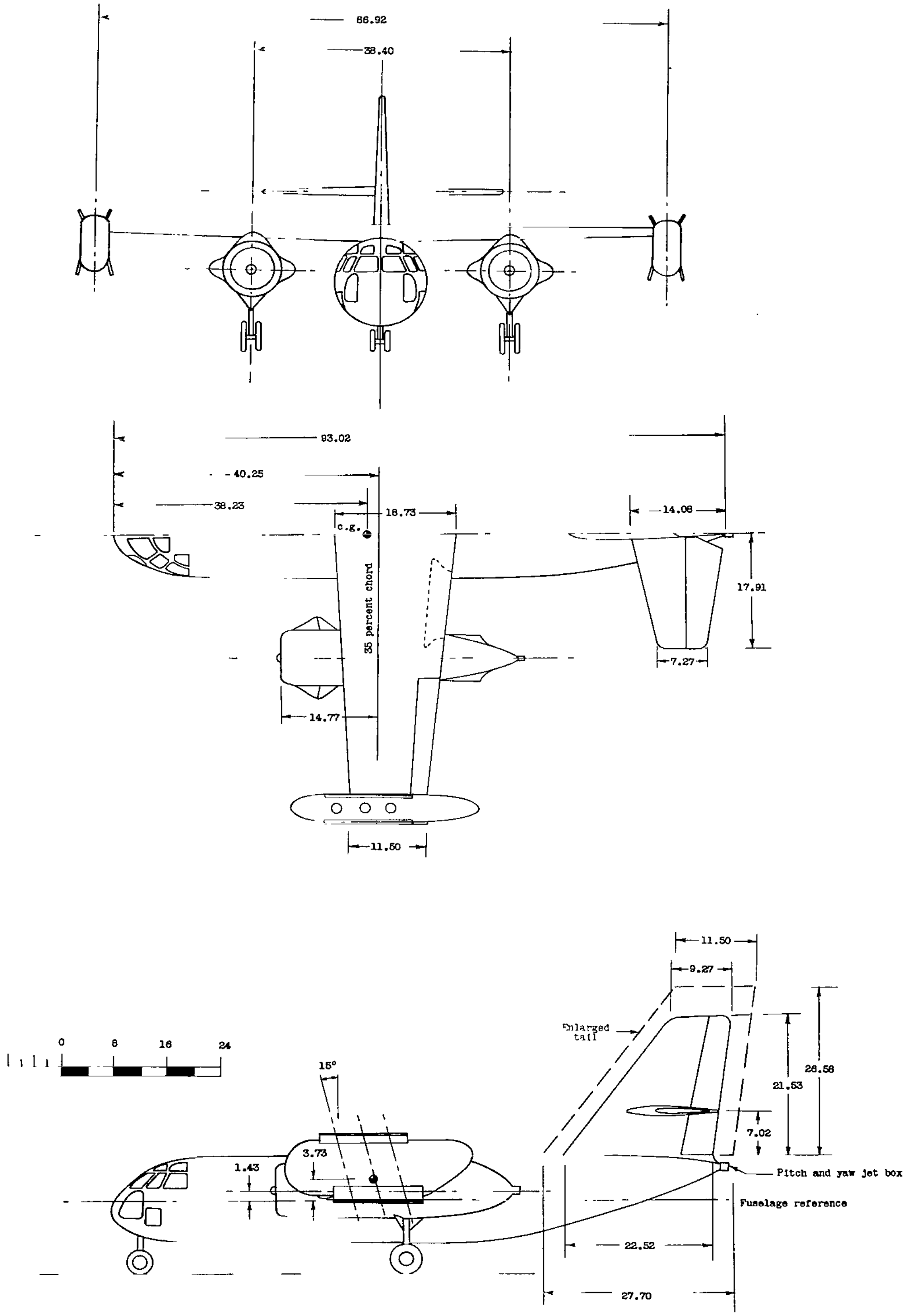
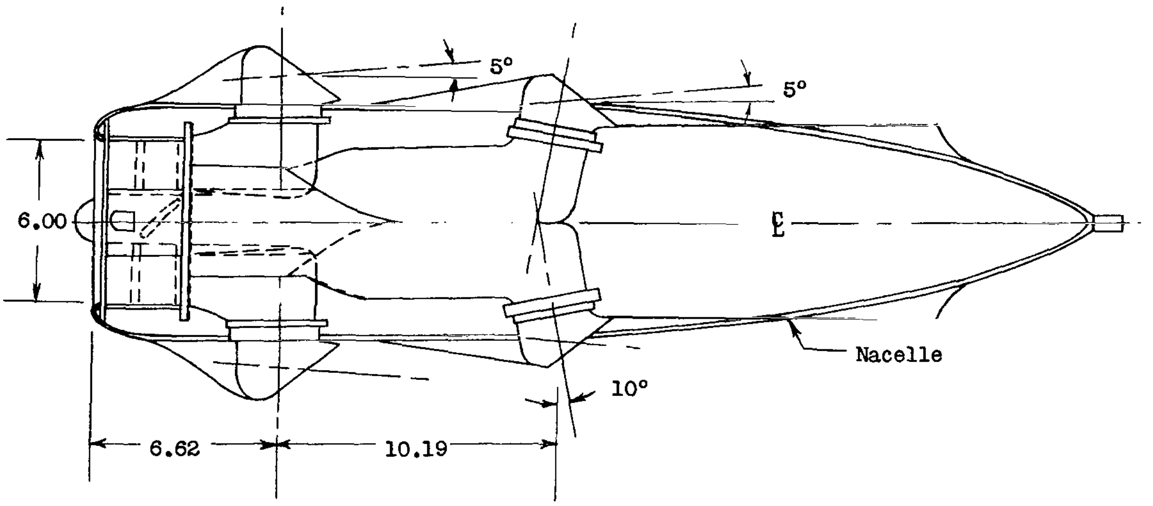
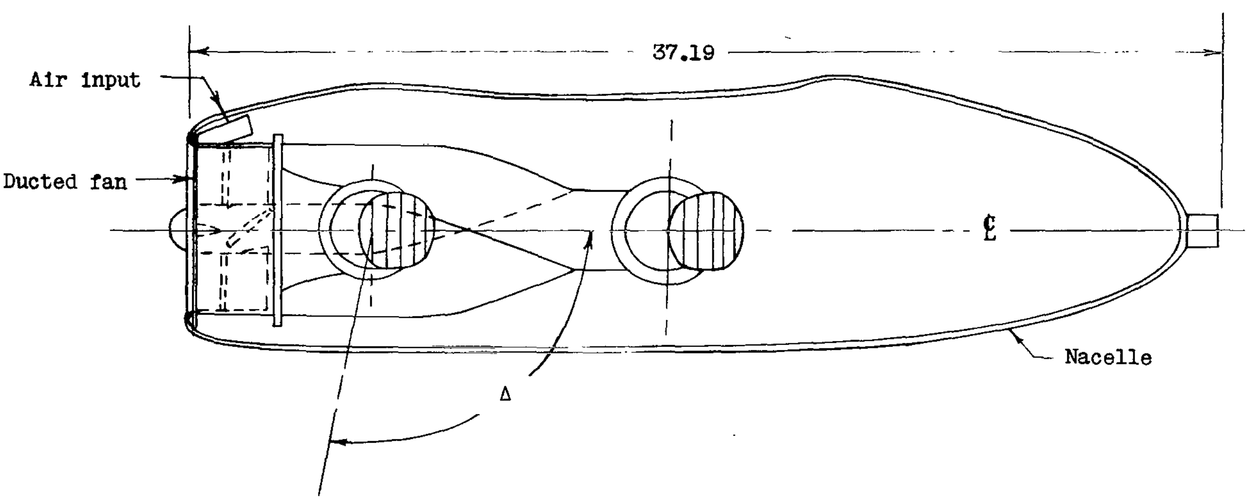


Figure 2.- Three-view sketch of model. All dimensions are in inches.



Top view

(Top half of nacelle removed)



Side view

(Side of nacelle removed)

Figure 3.- Sketches of simulated vectored-thrust engines used on model.

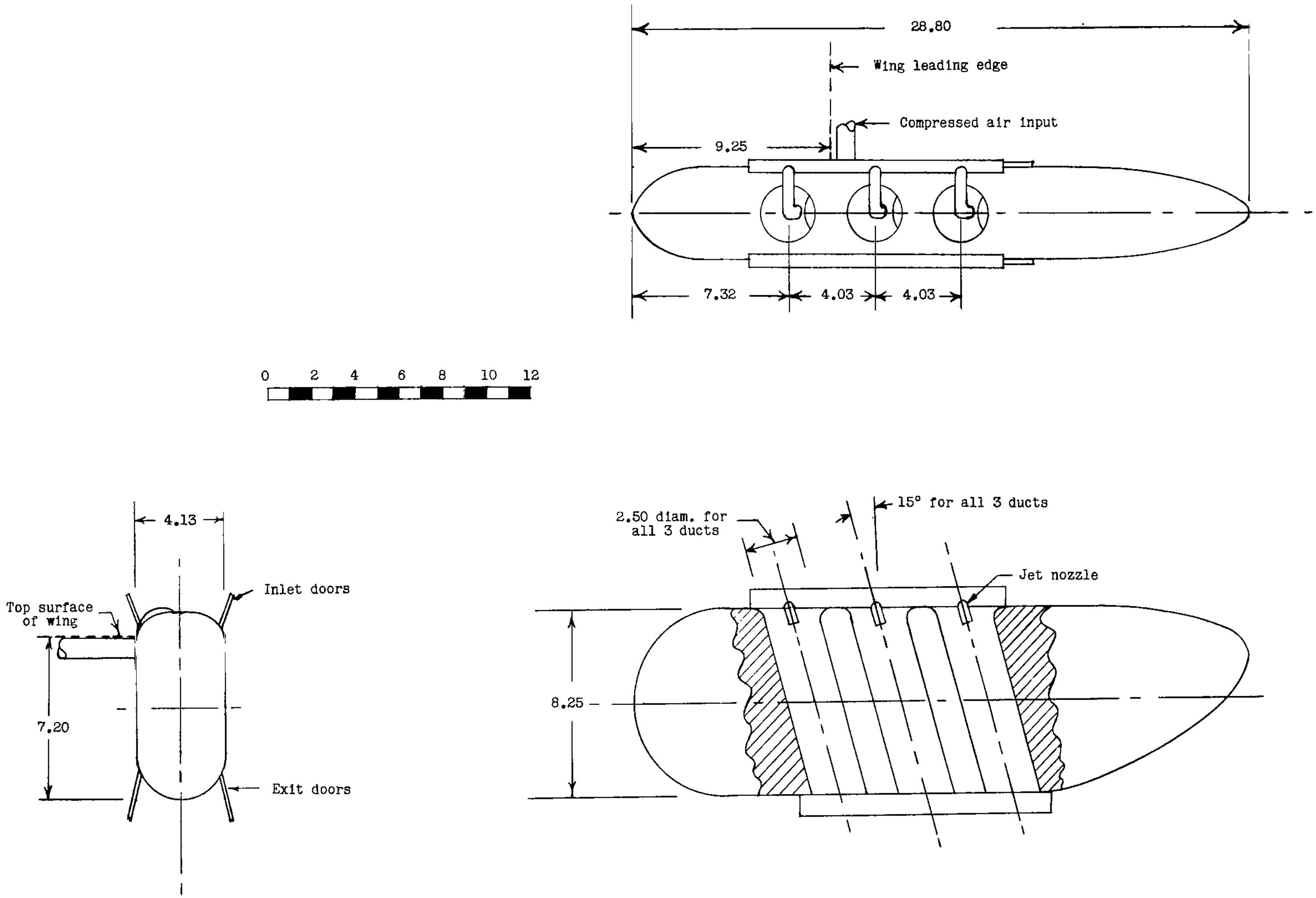


Figure 4.- Sketches showing simulated wing-tip lifting engines pod. All dimensions are in inches.

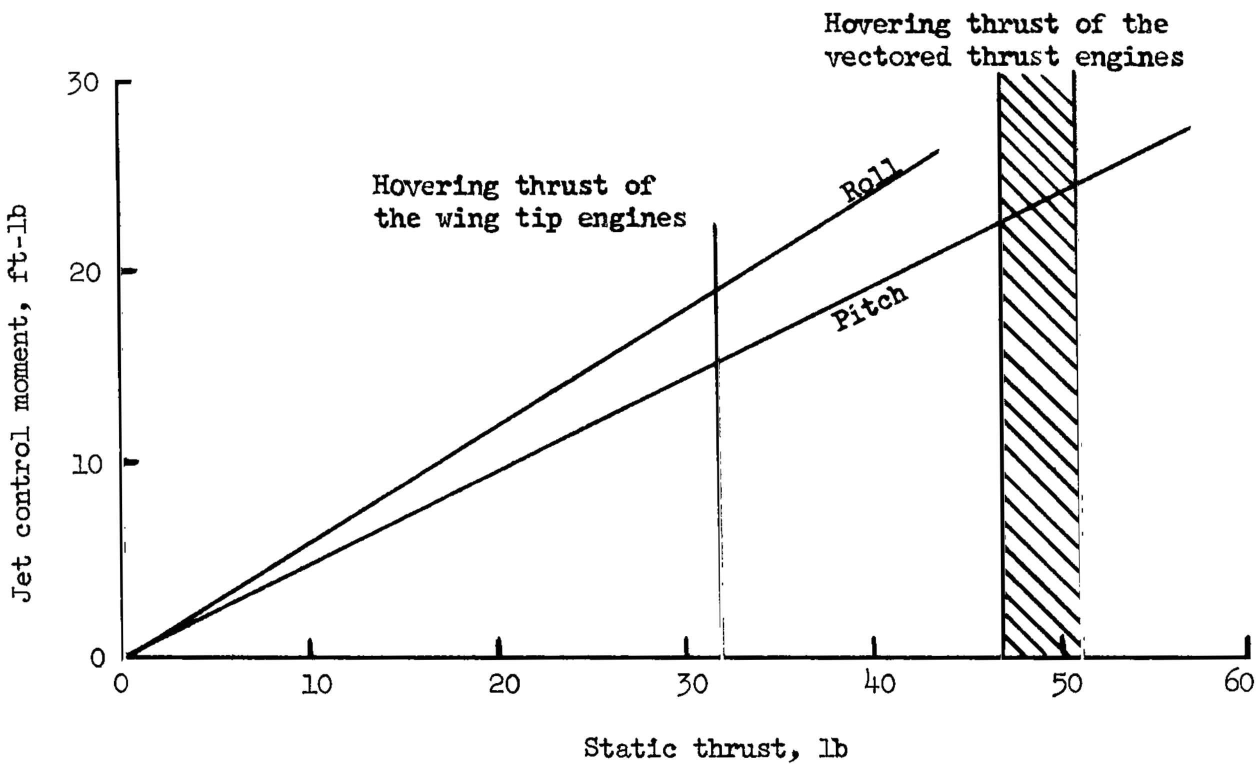


Figure 5.- Calibration of pitch and roll jet-reaction controls used on model.

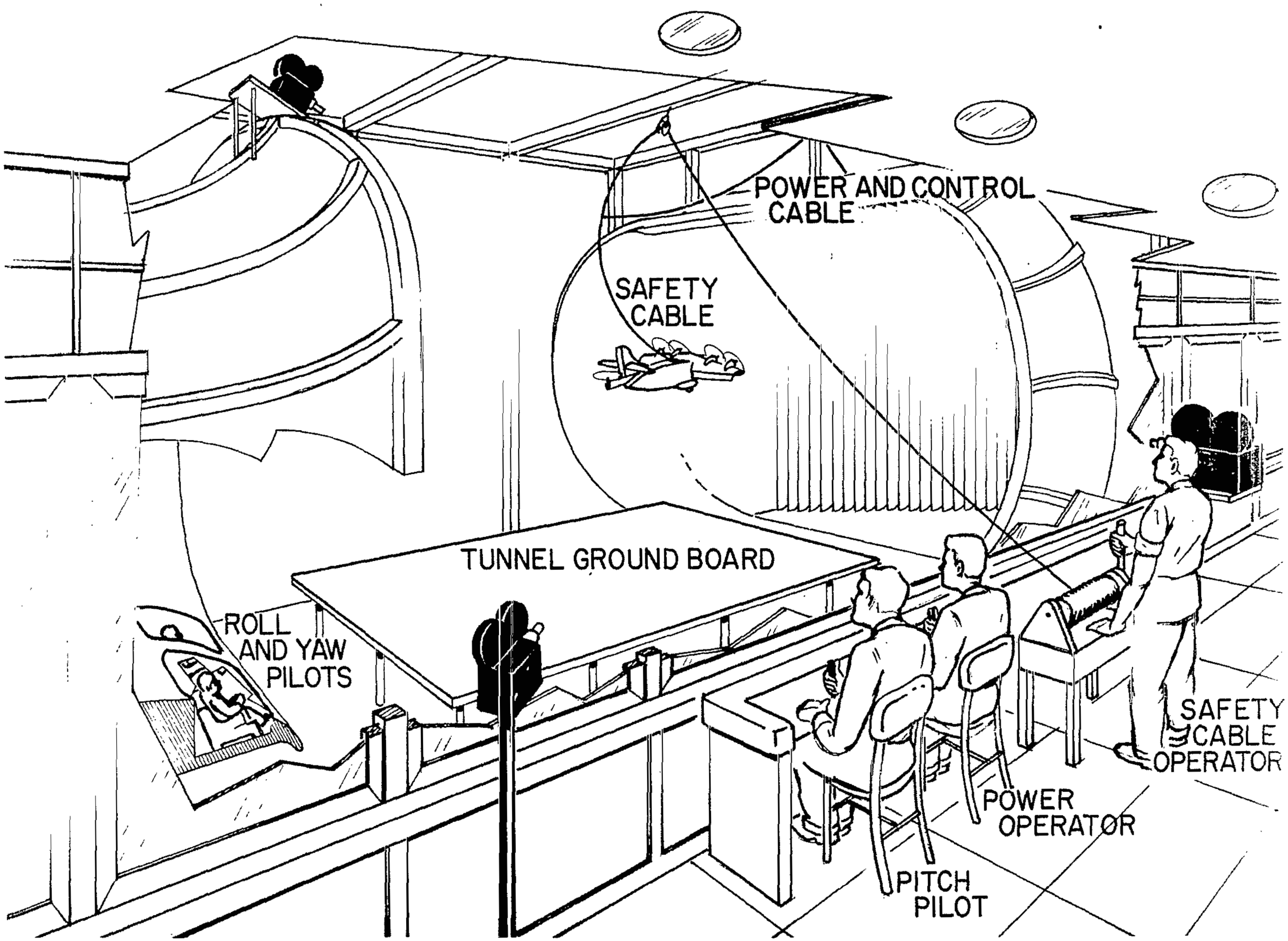


Figure 6.- Setup for flight tests in the Langley full-scale tunnel. L-64-3008

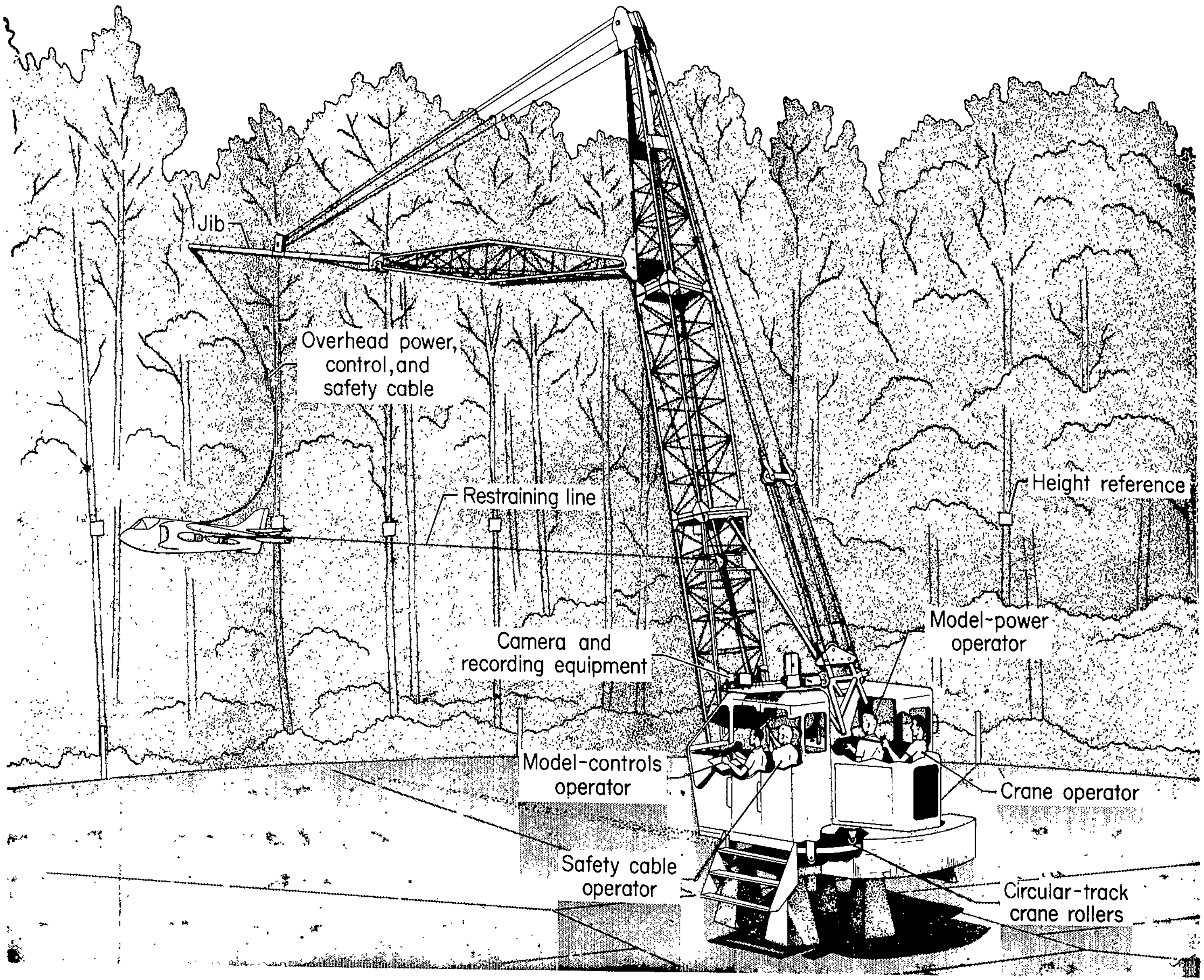
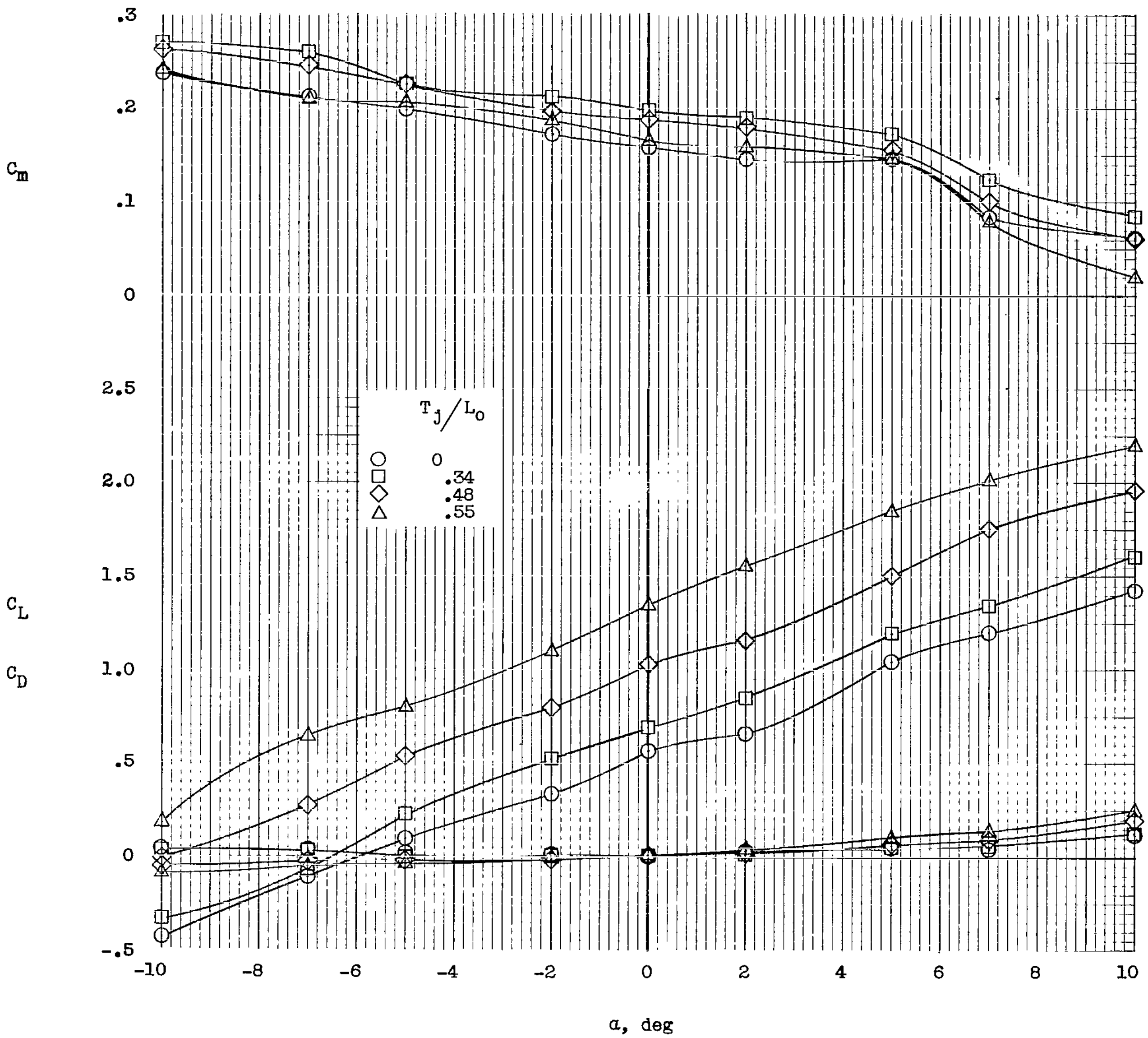
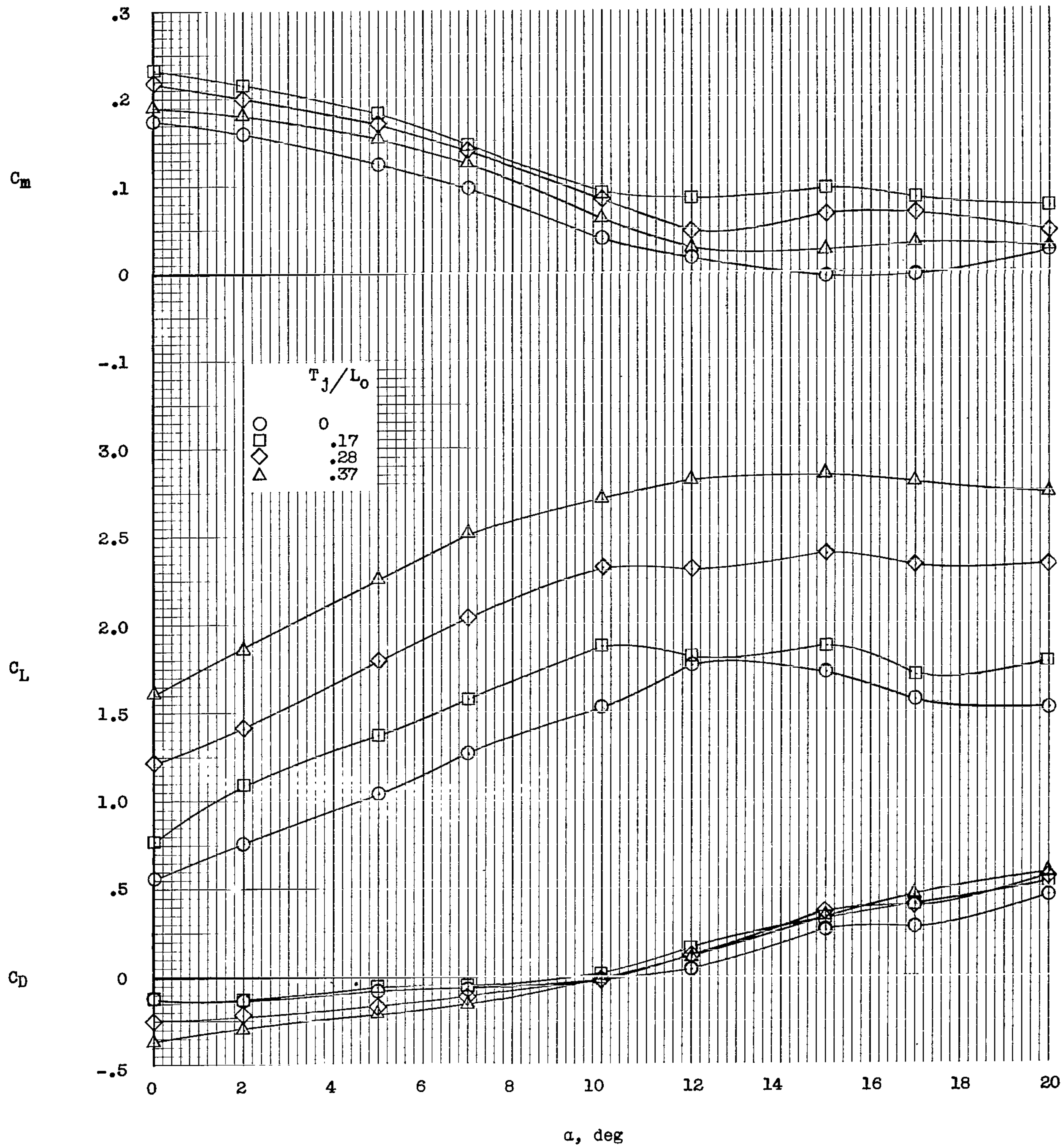


Figure 7.- The Langley control-line equipment.



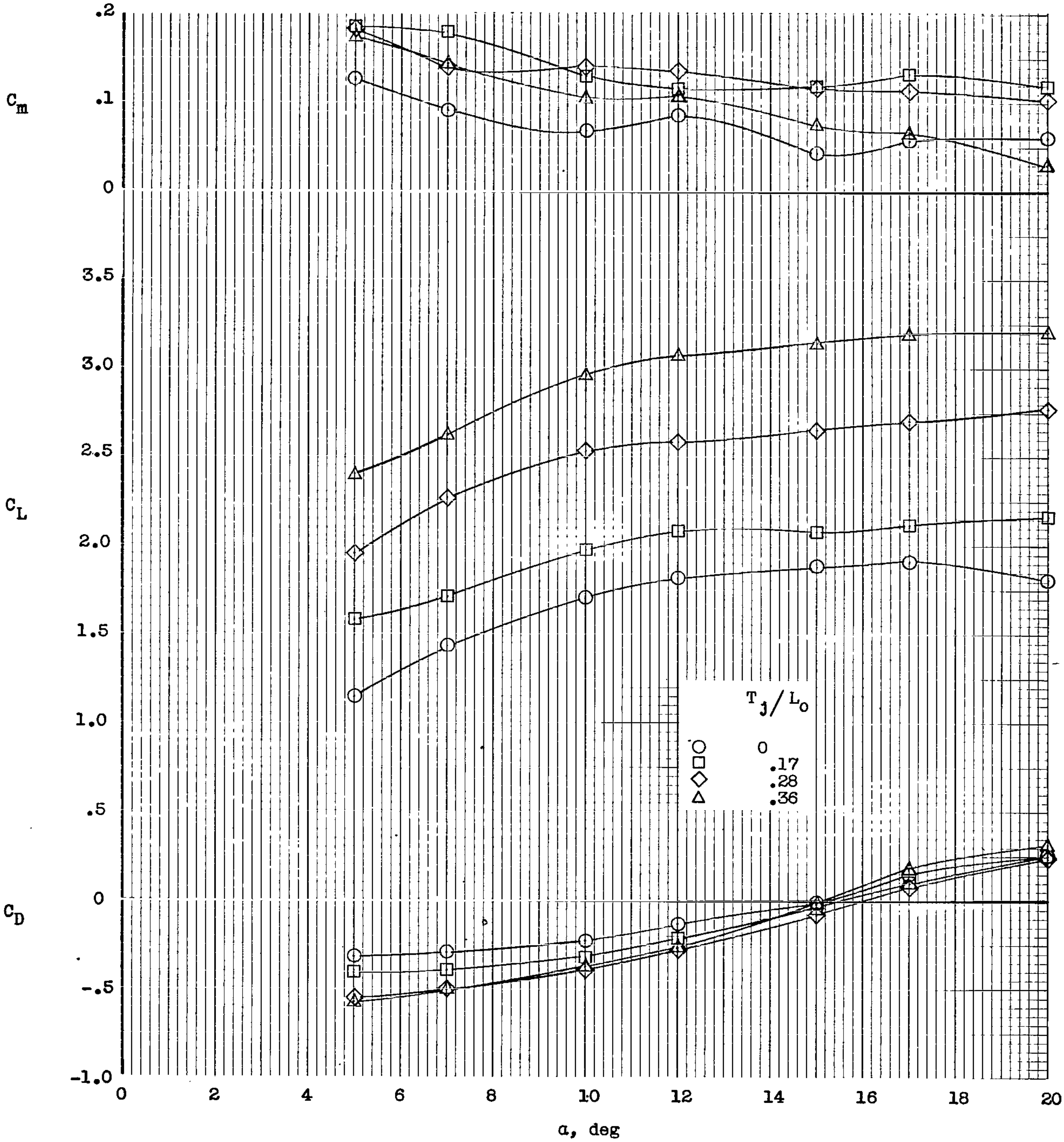
(a) Drag = 0 at $\alpha = 0^{\circ}$.

Figure 8.- Longitudinal force-test data for model. Referred to wind axis; $\delta_f = 60^{\circ}$; $\Delta = 0^{\circ}$.



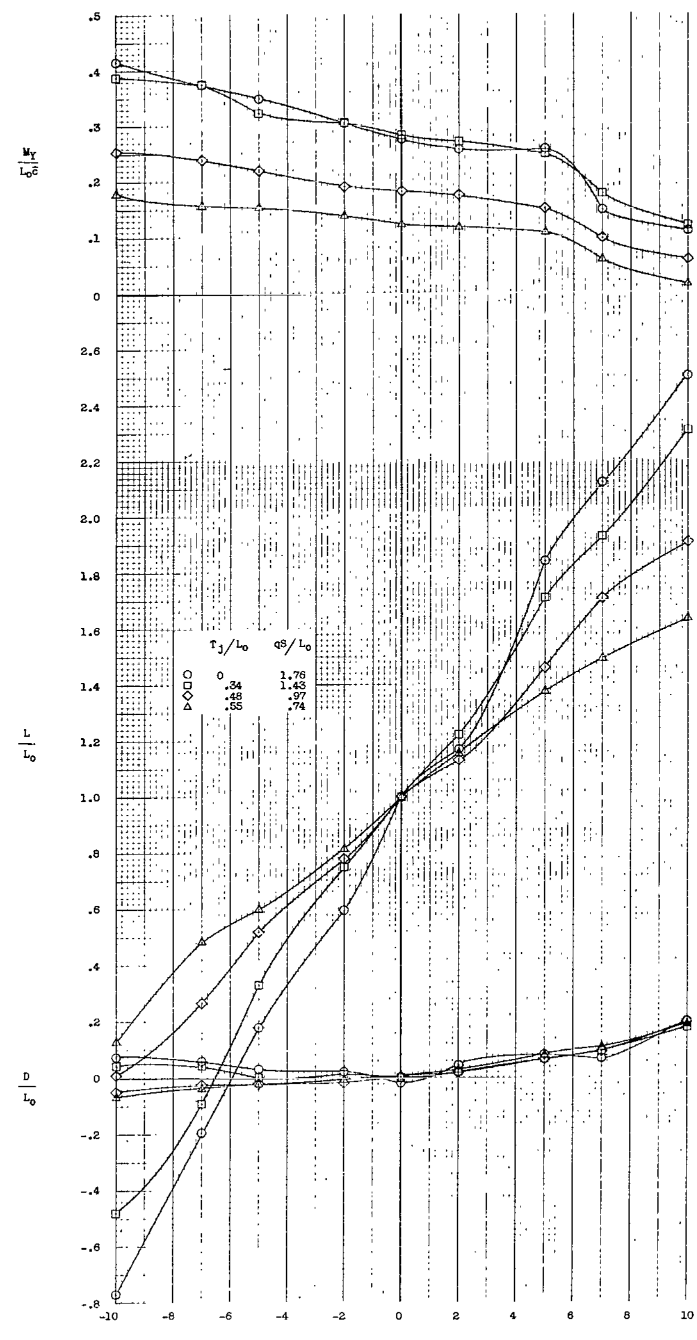
(b) Drag = 0 at α = 10°.

Figure 8.- Continued.



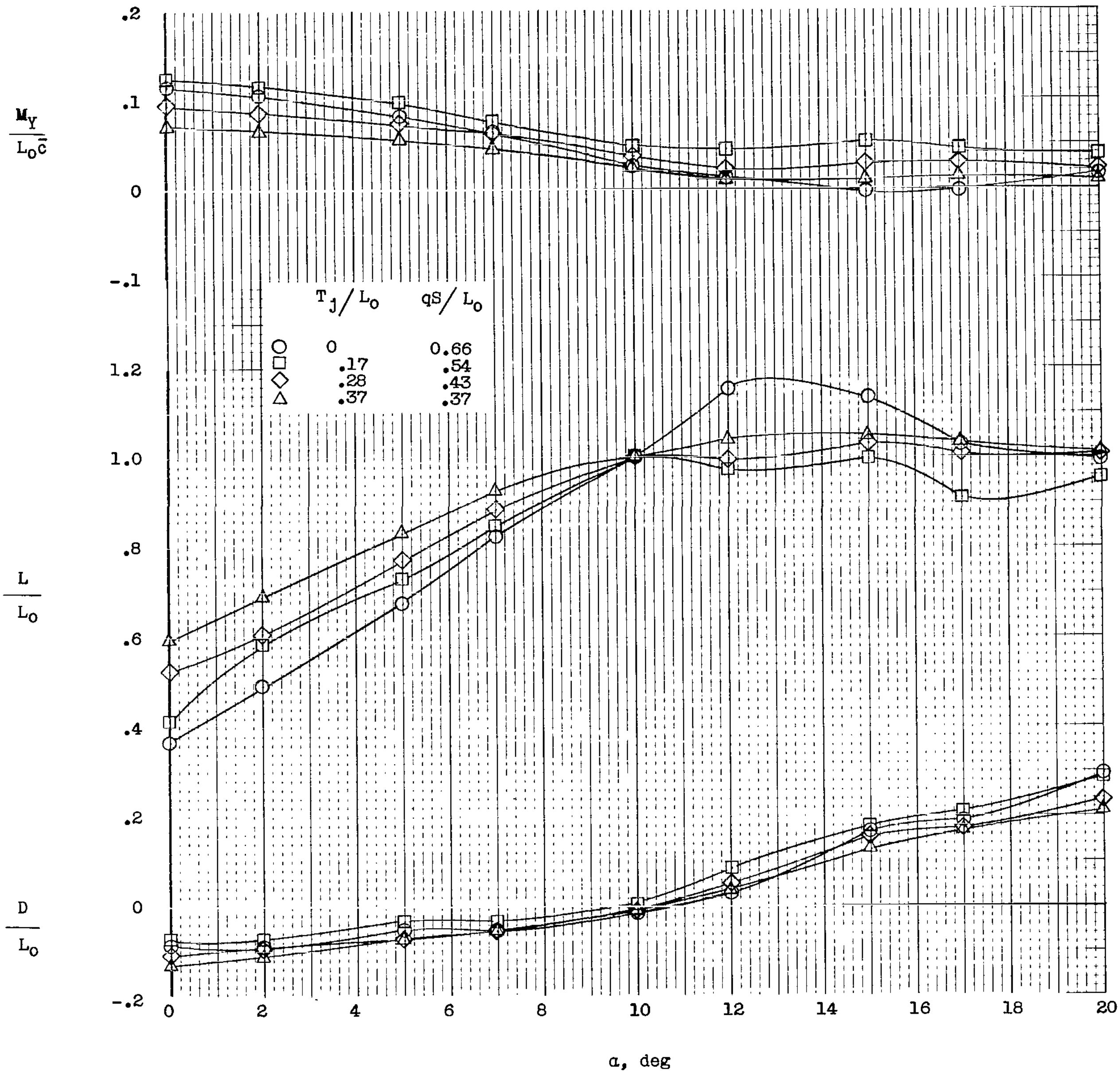
(c) Drag = 0 at $\alpha = 15^{\circ}$.

Figure 8.- Concluded.



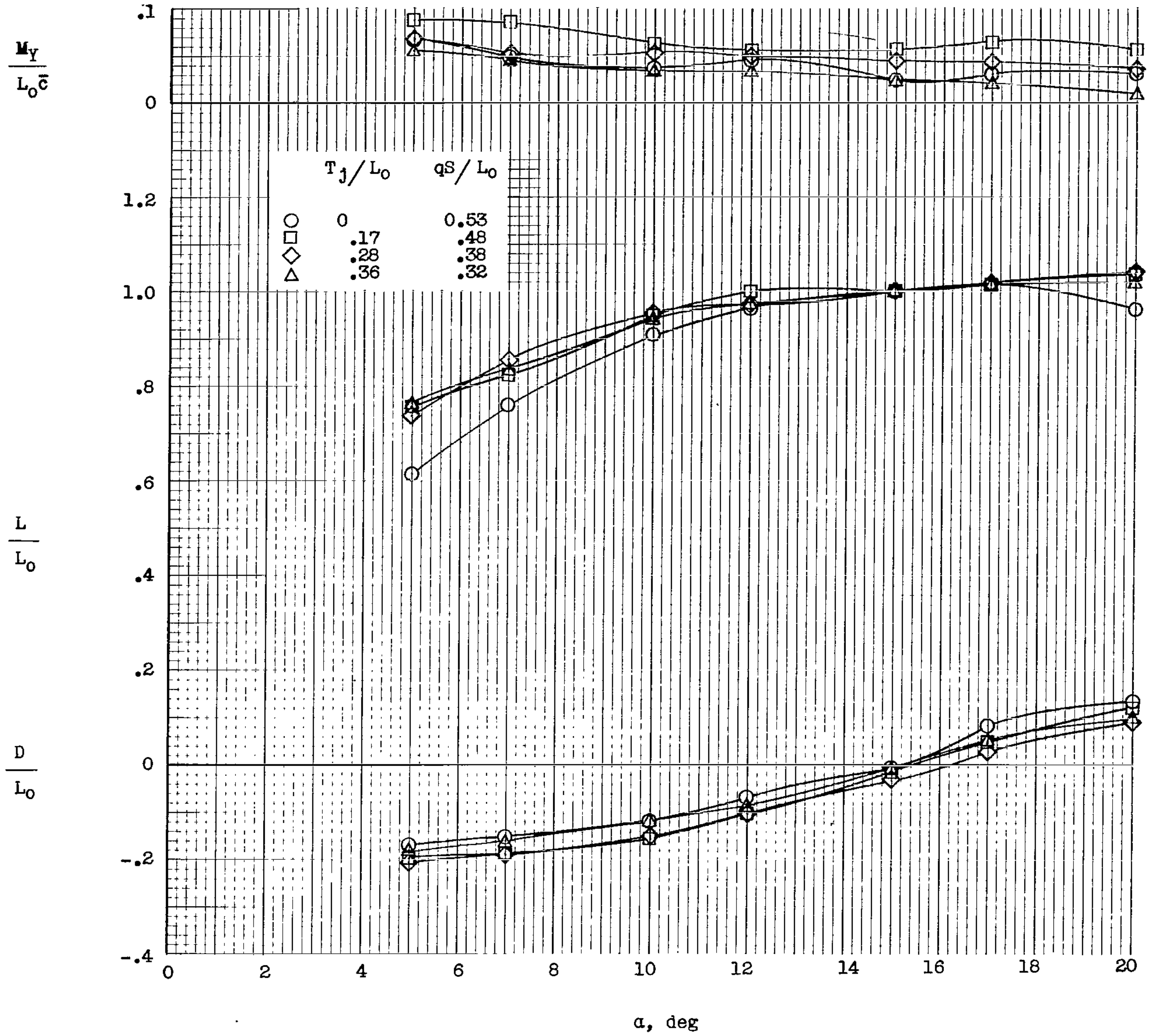
(a) Drag = 0 at $\alpha = 0^\circ$.

Figure 9.- Longitudinal force-test data for model. Referred to wind axis; $\delta_f = 60^\circ$; $\Delta = 0^\circ$.



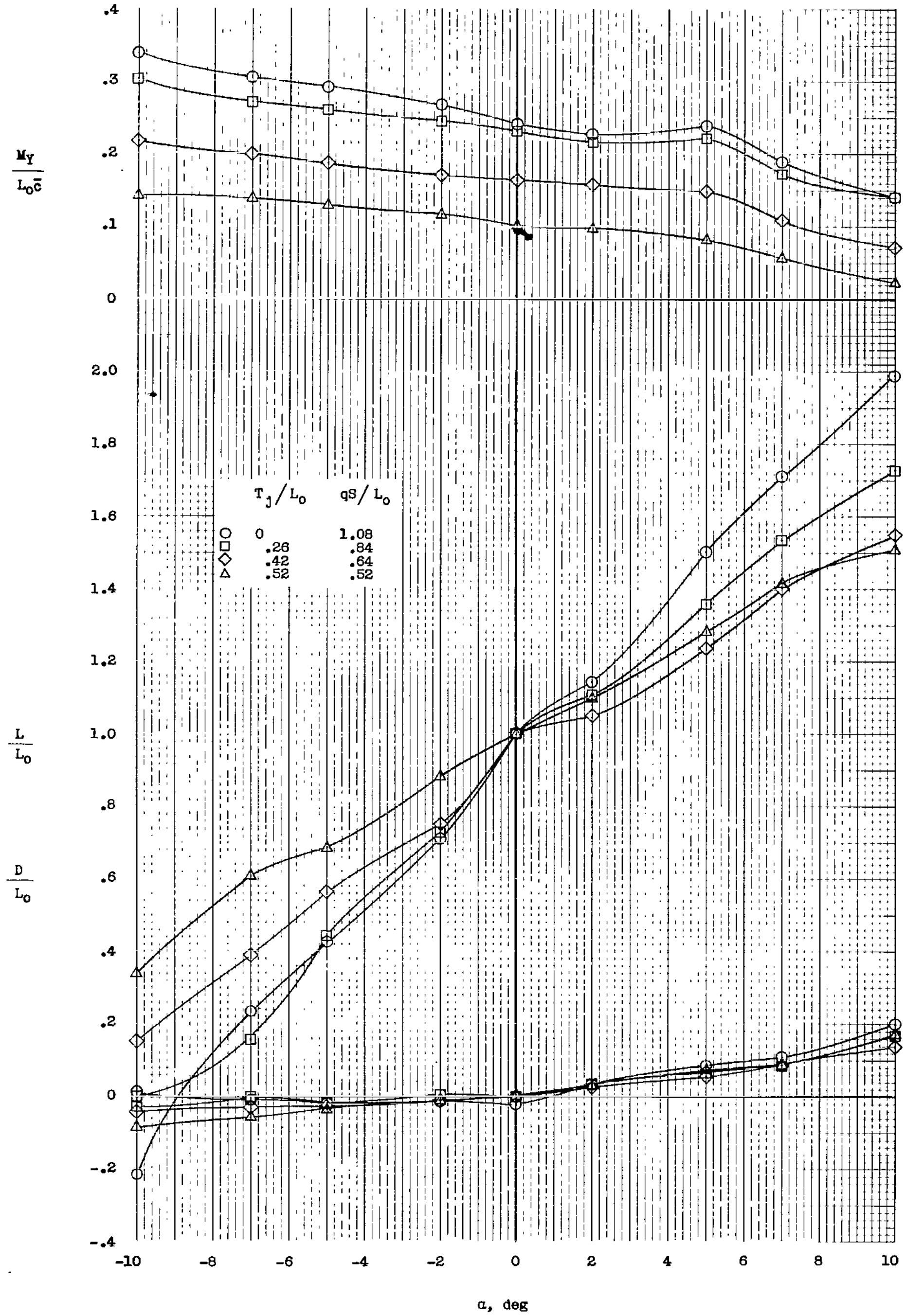
(b) Drag = 0 at $\alpha = 10^{\circ}$.

Figure 9.- Continued.



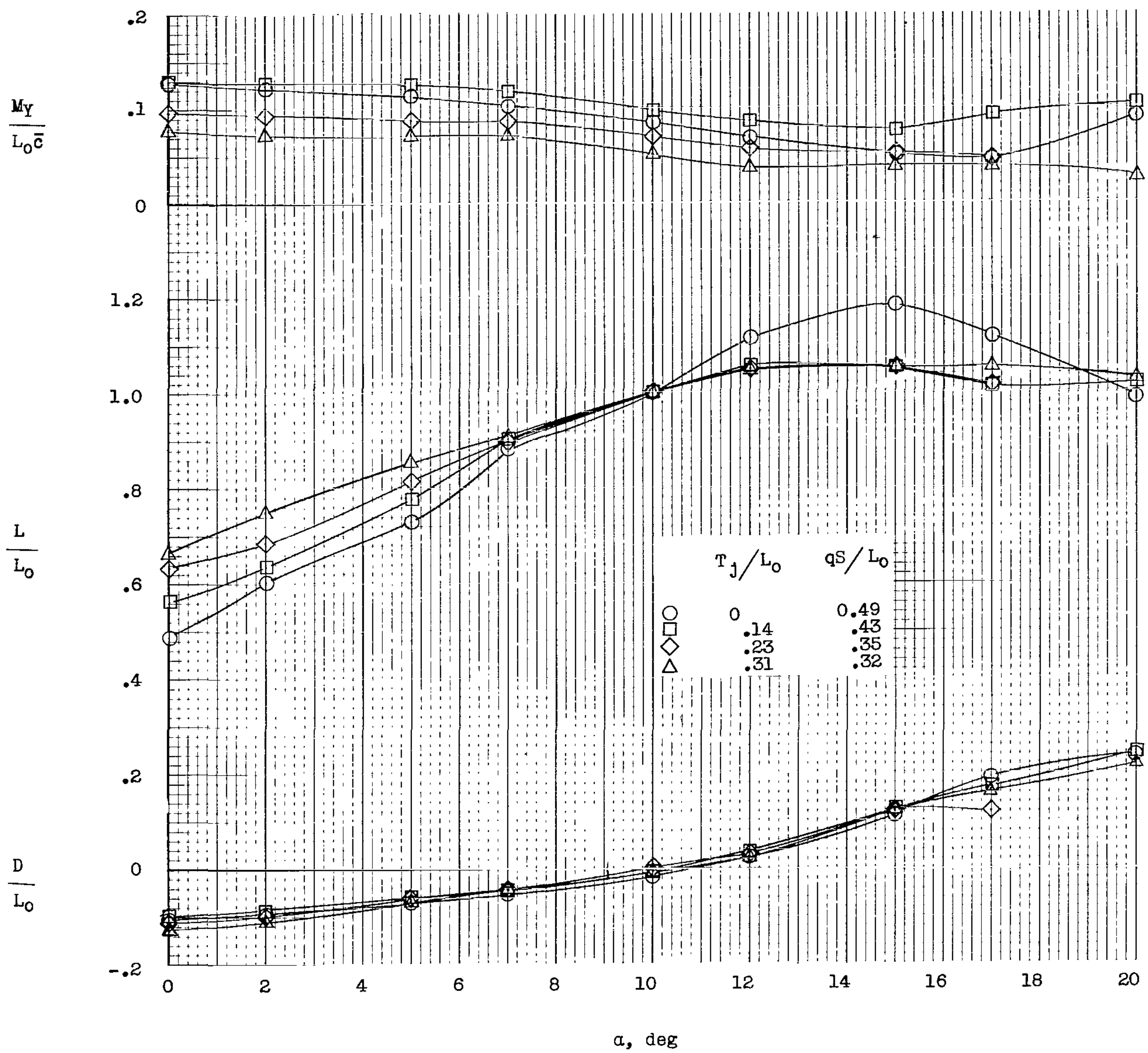
(c) Drag = 0 at $\alpha = 15^{\circ}$.

Figure 9.- Concluded.



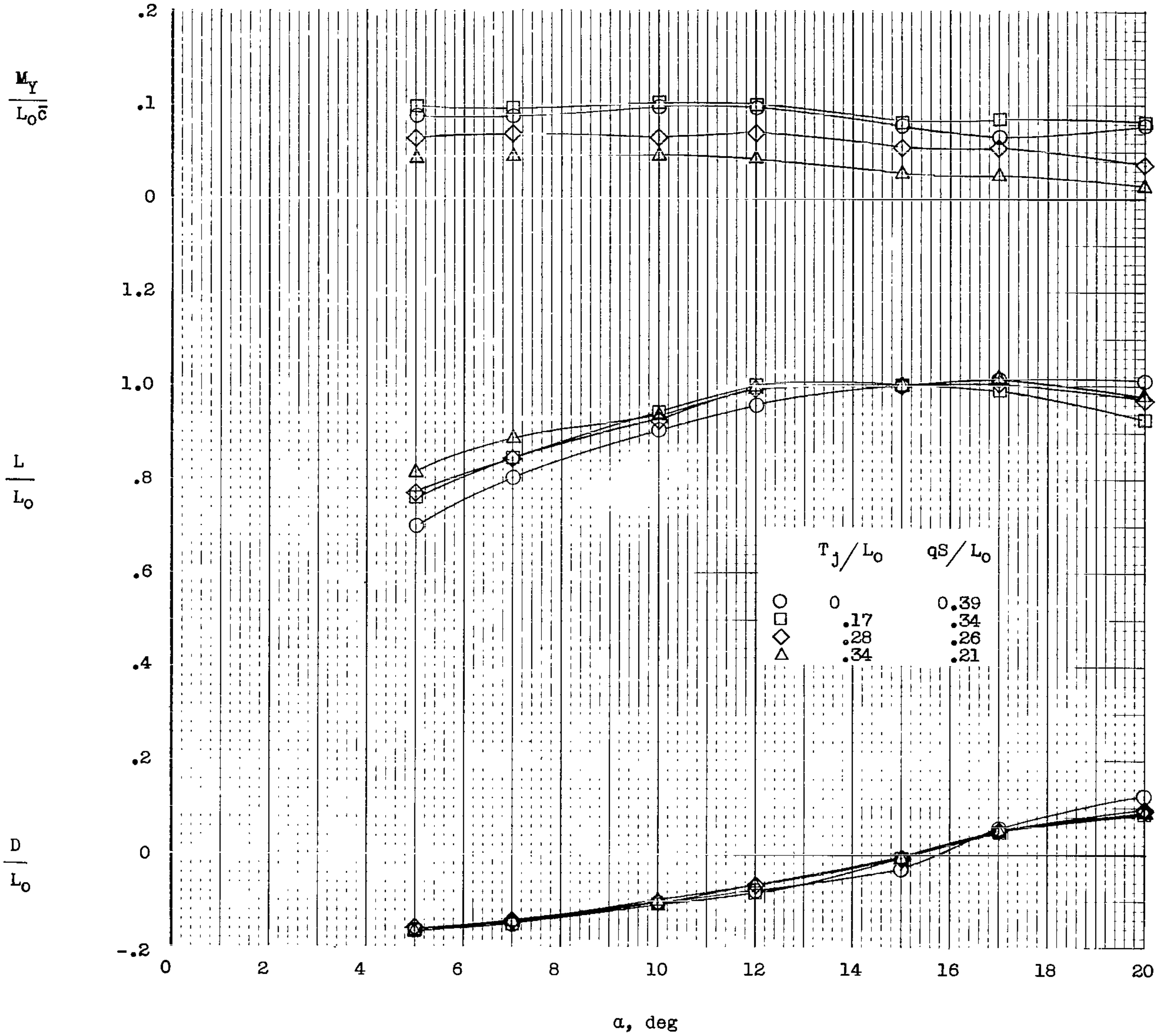
(a) Drag = 0 at $\alpha = 0^\circ$.

Figure 10.- Longitudinal force-test data for model. Referred to wind axis; $\delta_f = 60^\circ$; $\Delta = 30^\circ$.



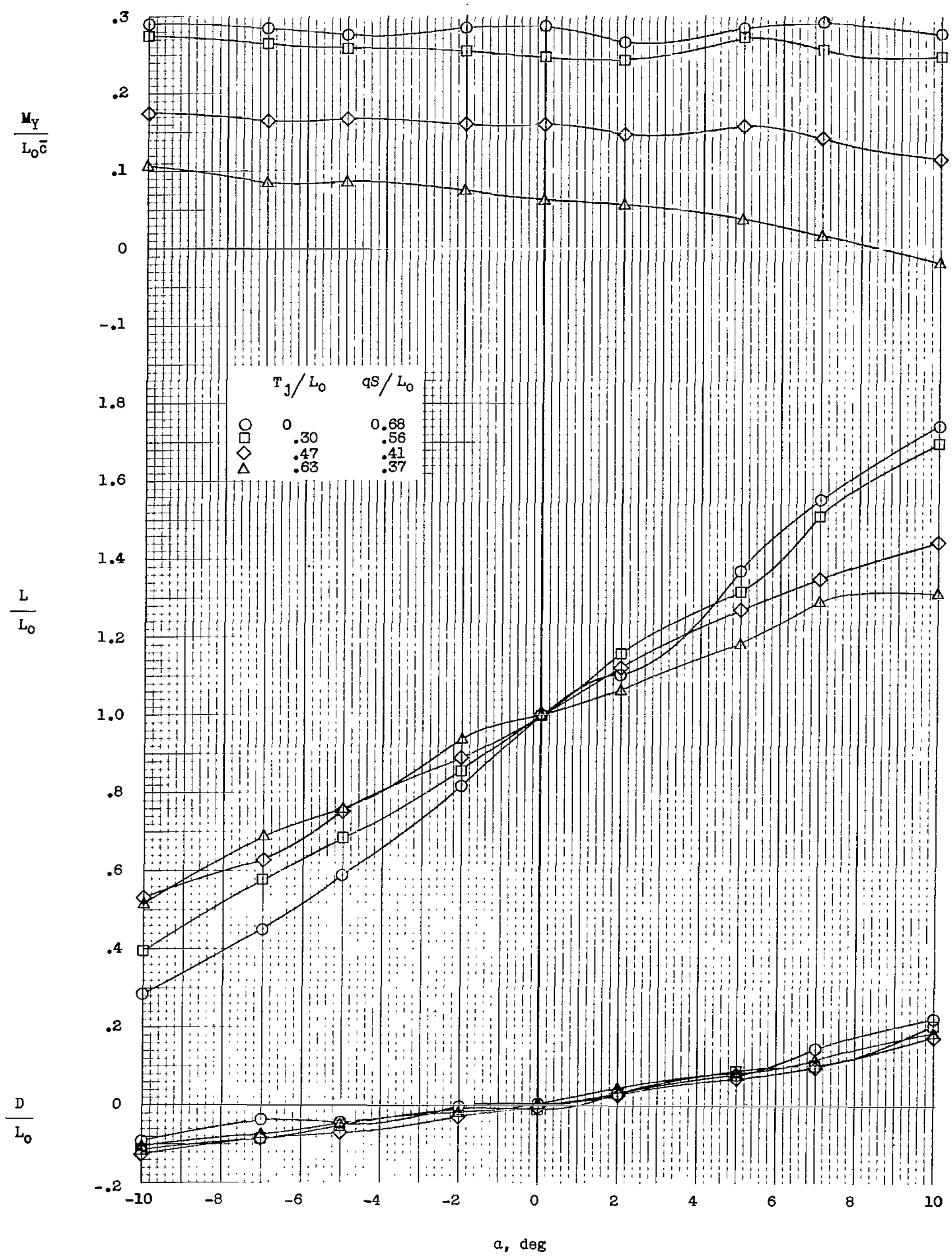
(b) Drag = 0 at $\alpha = 10^{\circ}$.

Figure 10.- Continued.



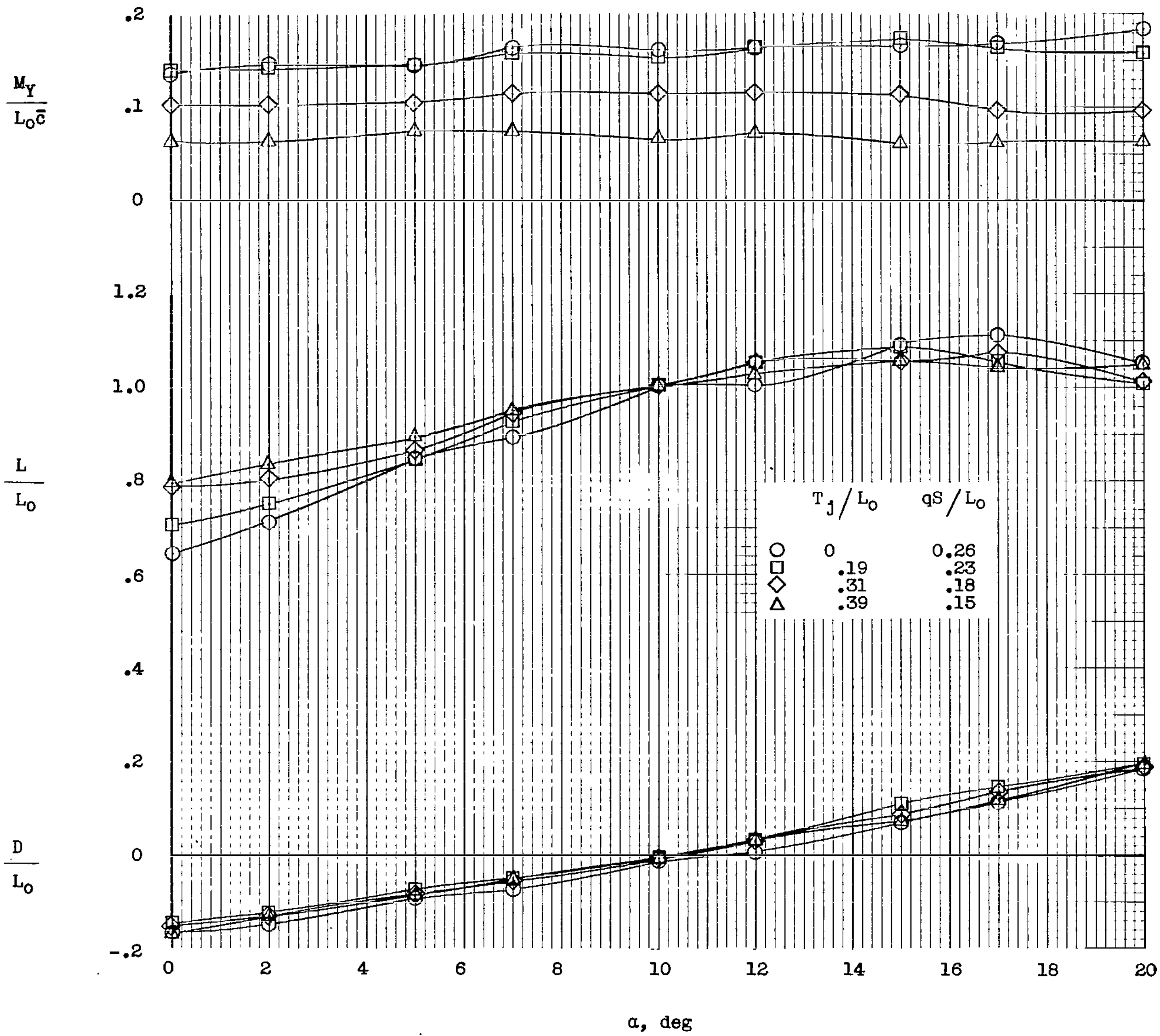
(c) Drag = 0 at $\alpha = 15^{o}$.

Figure 10.- Concluded.



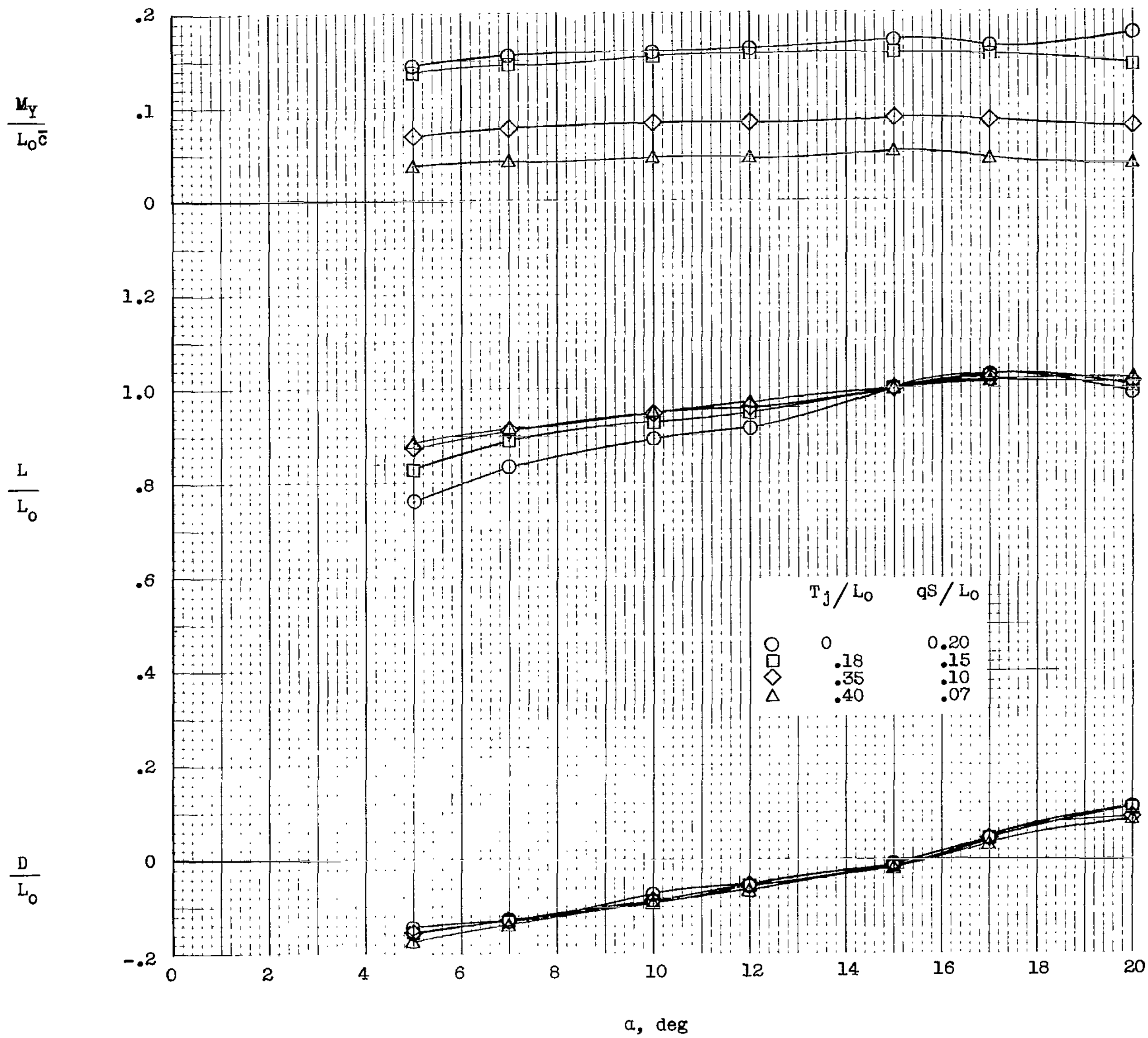
(a) Drag = 0 at α = 0°.

Figure 11.- Longitudinal force-test data for model. Referred to wind axis; $\delta_f = 60^\circ$; $\Delta = 60^\circ$.



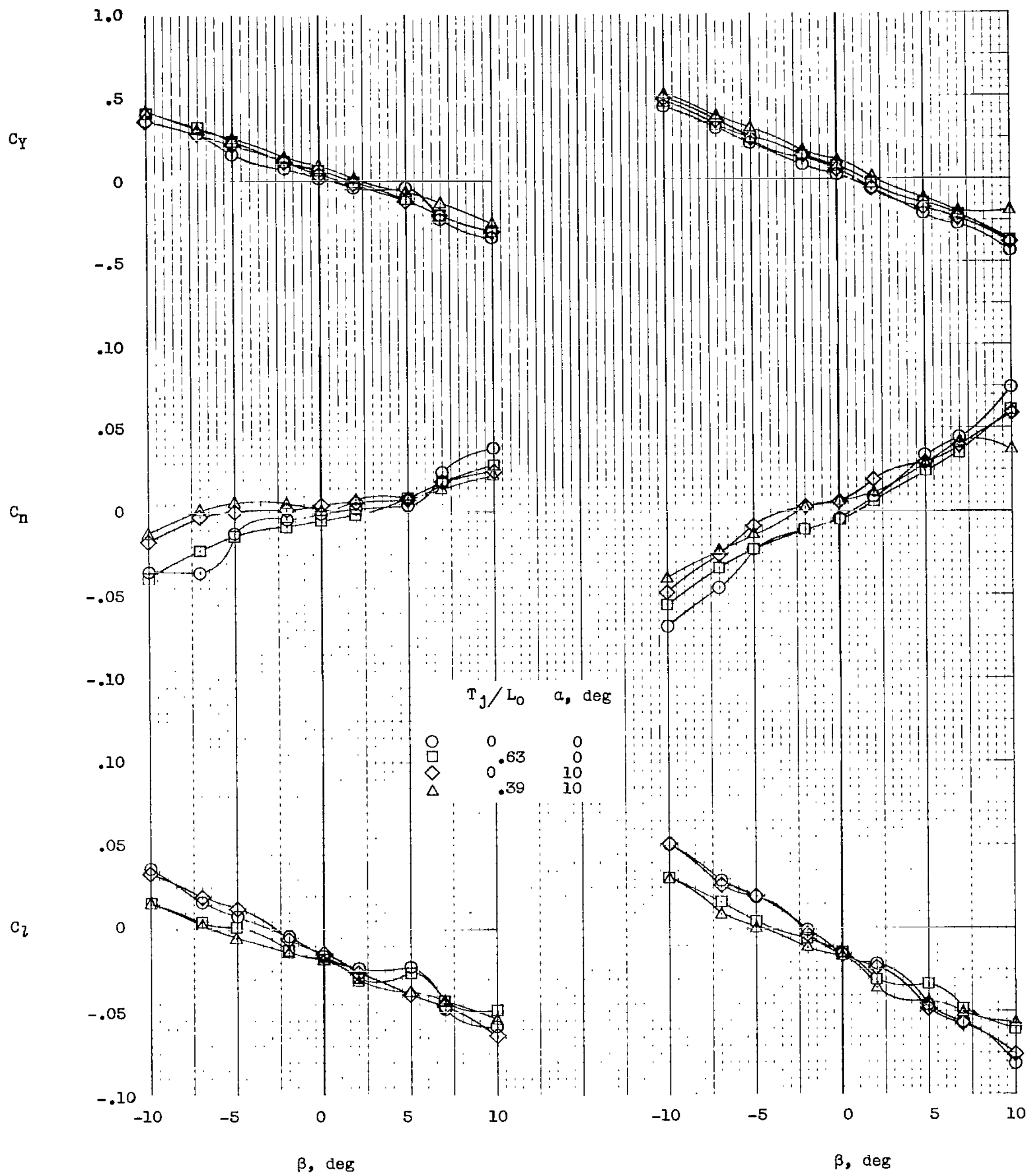
(b) Drag = 0 at $\alpha = 10^{\circ}$.

Figure 11.- Continued.



(c) Drag = 0 at $\alpha = 15^{\circ}$.

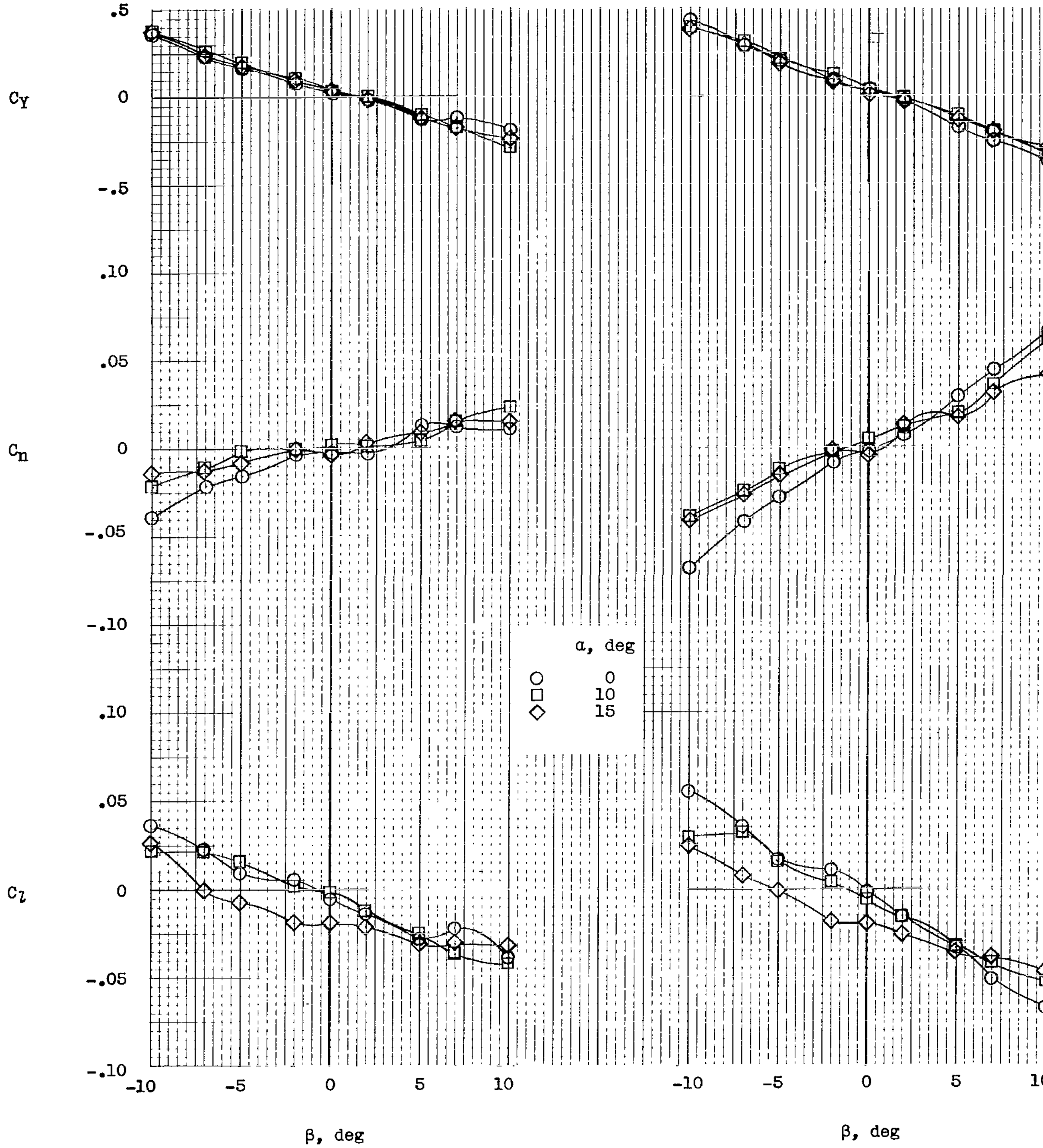
Figure 11.- Concluded.



(a) Basic model.

(b) Vertical-tail area increased 50 percent.

Figure 12.- Lateral force-test data. Referred to body axis; $\delta_f = 60^\circ$; $\Delta = 0^\circ$.



(a) Basic model.

(b) Vertical-tail area increased 50 percent.

Figure 13.- Lateral force-test data. Model power off; referred to body axis. $\delta_f = 60^\circ$.

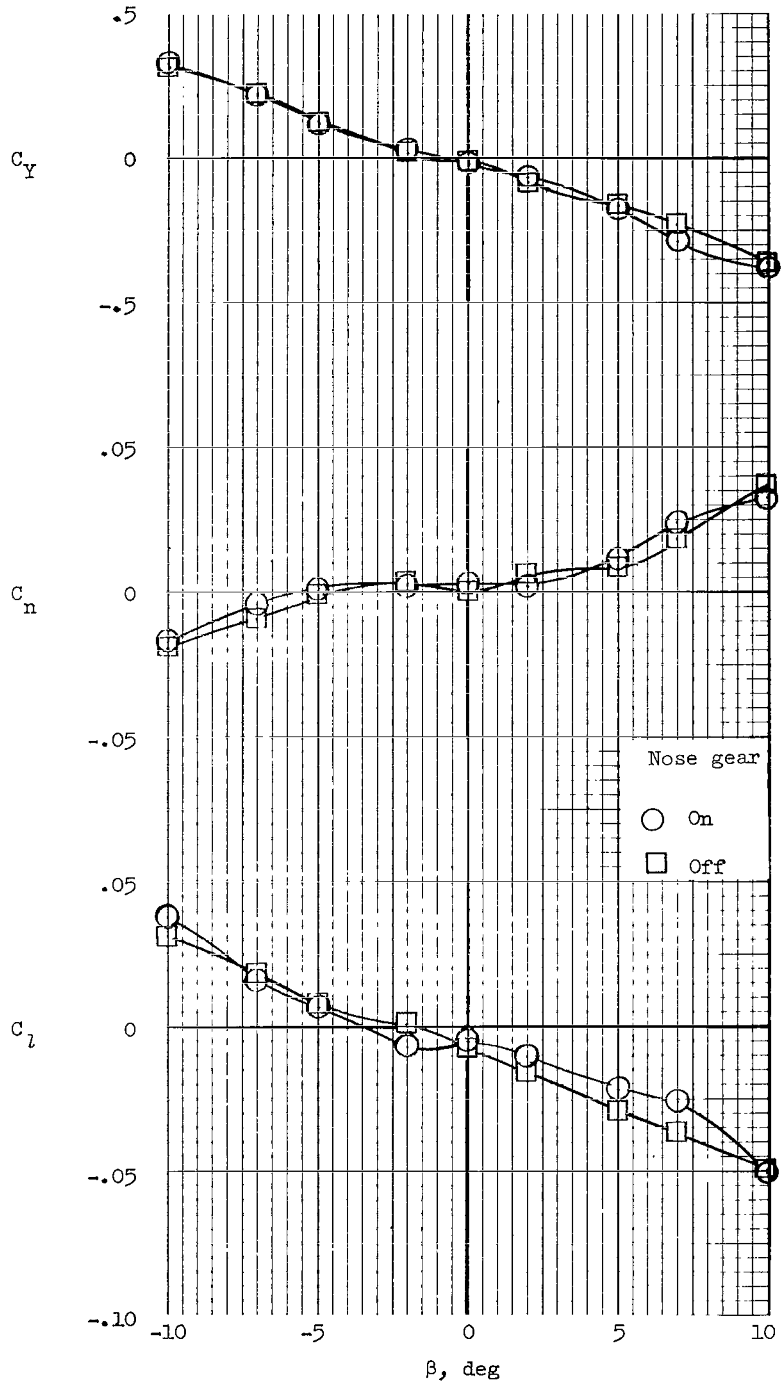


Figure 14.- Lateral force-test data for model with and without nose landing gear. Referred to body axis; $T_j/L_o = 0$; drag = 0 at $\alpha = 0^{\circ}$; $\Delta = 0^{\circ}$; $\delta_f = 0^{\circ}$.

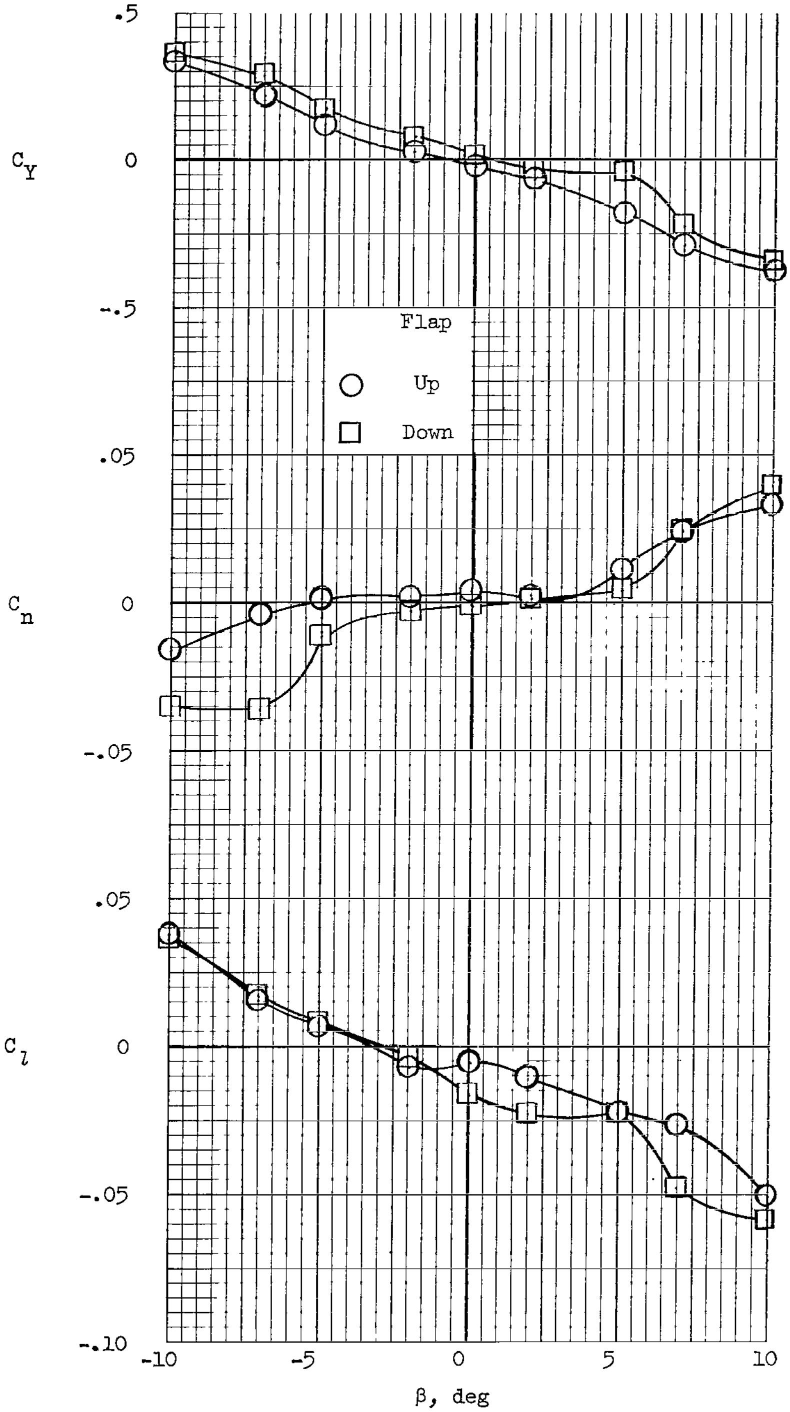


Figure 15.- Lateral force-test data for model in flaps-up and flaps-down condition. Referred to body axis; $T_j/L_o = 0$; drag = 0 at $\alpha = 0^o$; $\Delta = 0^o$.

NASA-Langley, 1964 L-3956